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MAX-PLANCK-INSTITUT FÜR METEOROLOGIE

Coastal permafrost erosion & the future Arctic Ocean's CO_2 uptake

David Nielsen, Fatemeh Chegini, Joeran Maerz, Armineh Barkhordarian, Sebastian Brune, Paul Overduin, Patrick Pieper, Mikhail Dobrynin, Victor Brovkin, Johanna Baehr, Tatiana Ilyina

Barcelona, 6 June 2023

DFG Deutsche Forschungsgemeinschaft

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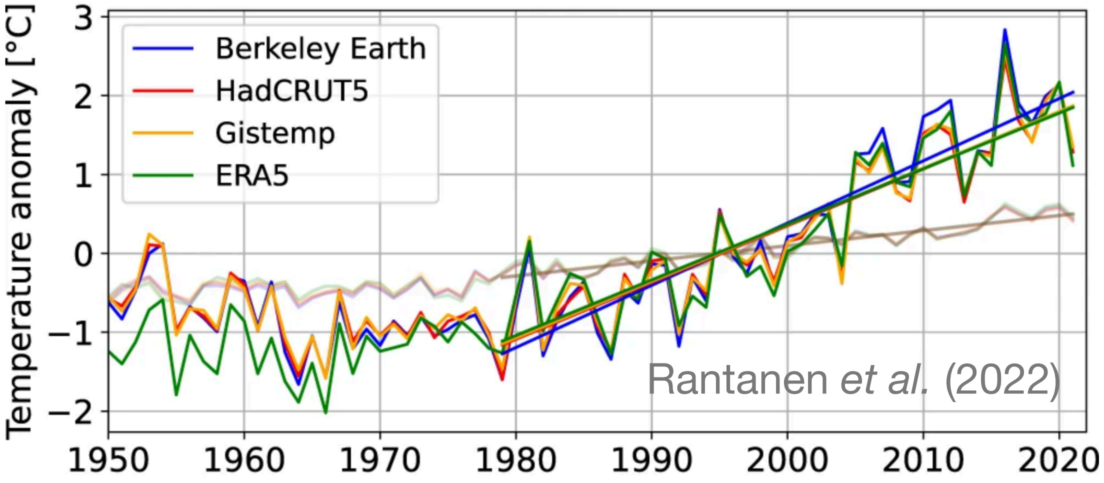
- Abrupt permafrost thaw contributes to warming via the **permafrost-climate feedback**

(Turetsky et al. 2019, 2020)

The Arctic has warmed about 4 times faster than the globe



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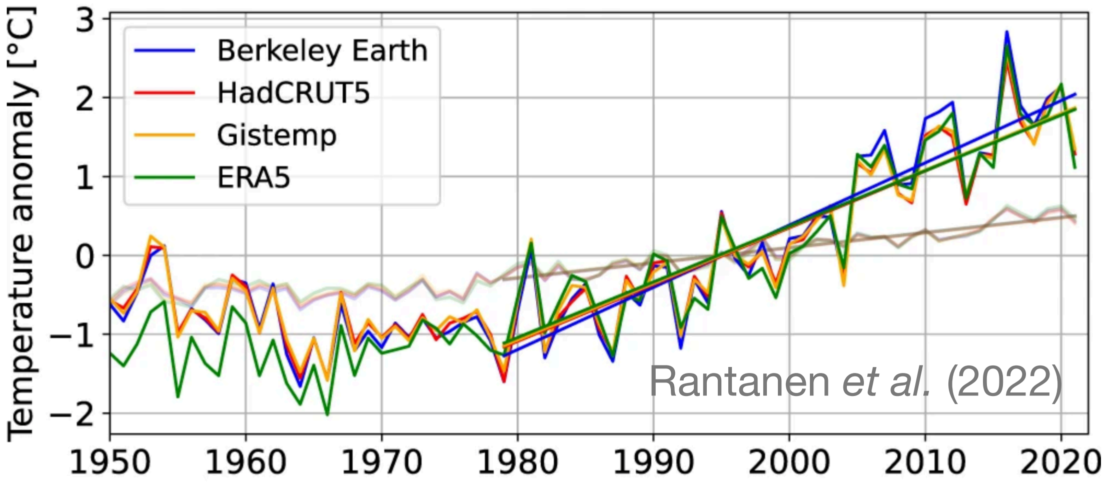

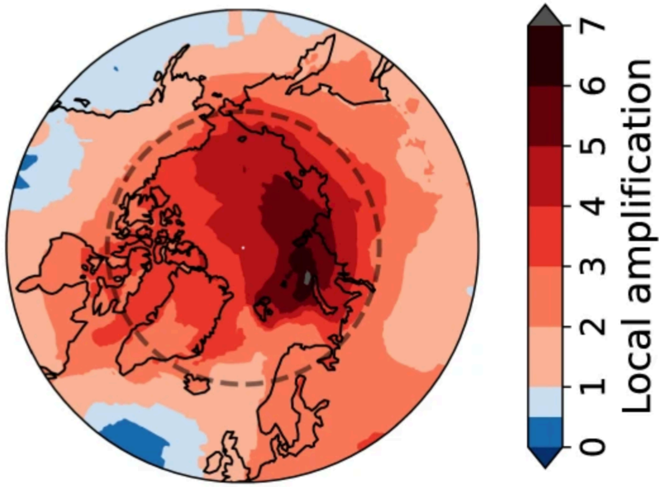

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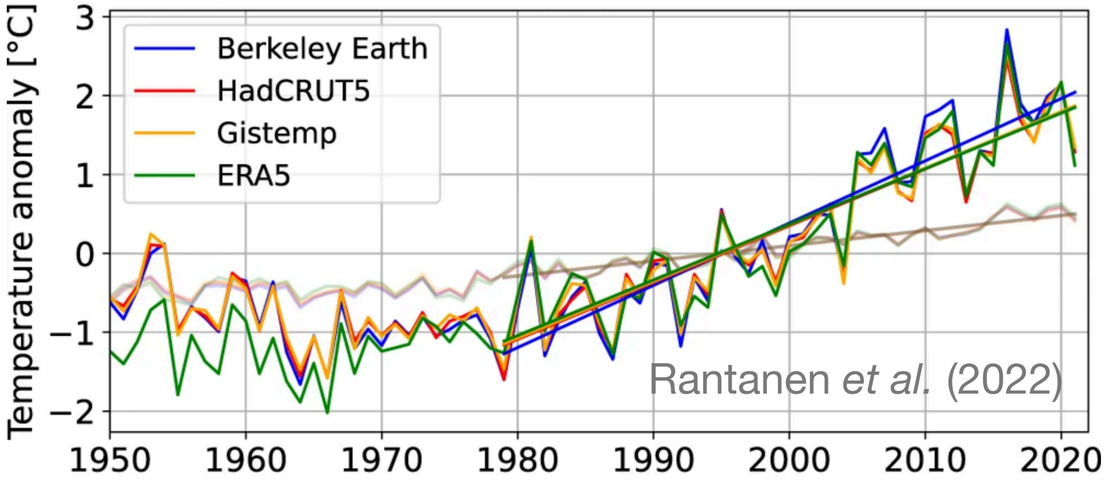

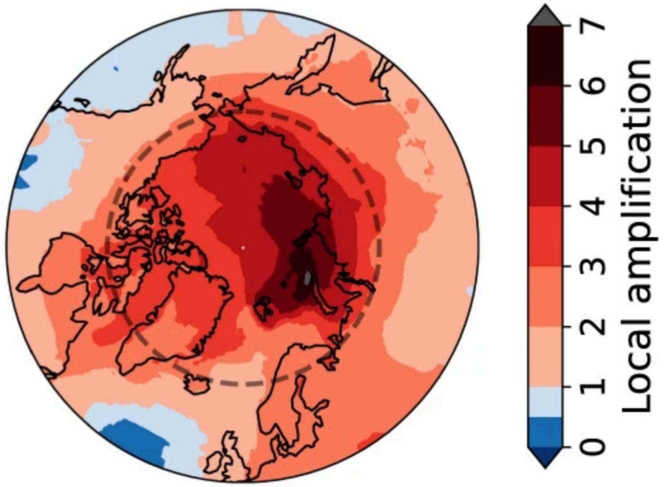

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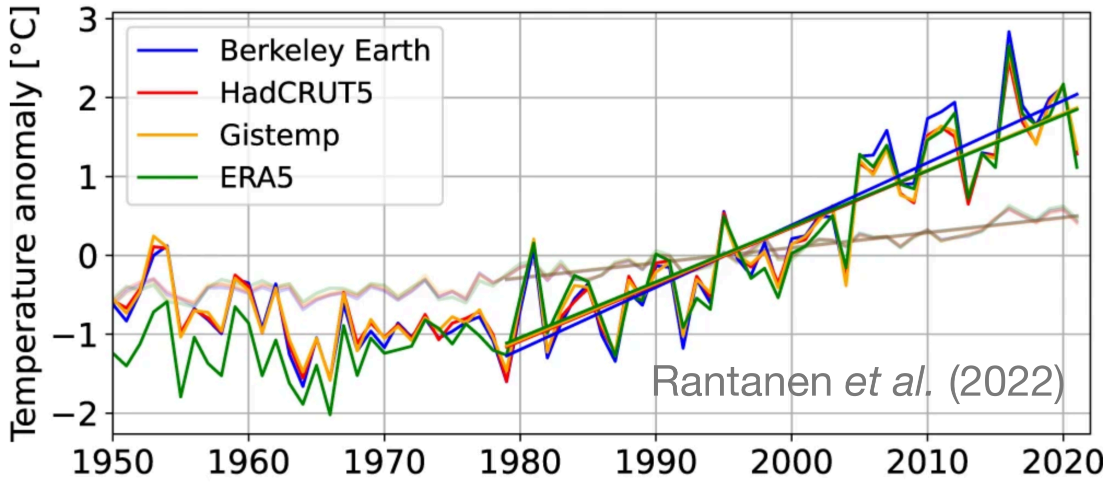

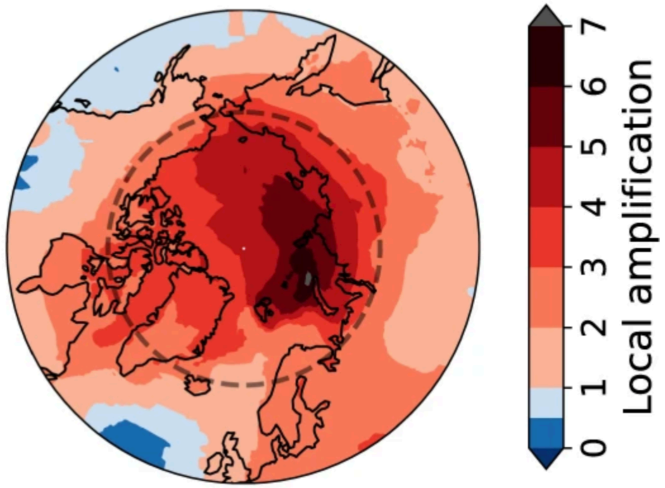

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How will Arctic coastal permafrost erosion change in the future?

Drivers of coastal permafrost erosion

Sea Ice

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Sea Ice → Open-water season

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Thermo-denudation

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Adapted from Günther et al. (2015) in *"Observing Muostakh disappear"*

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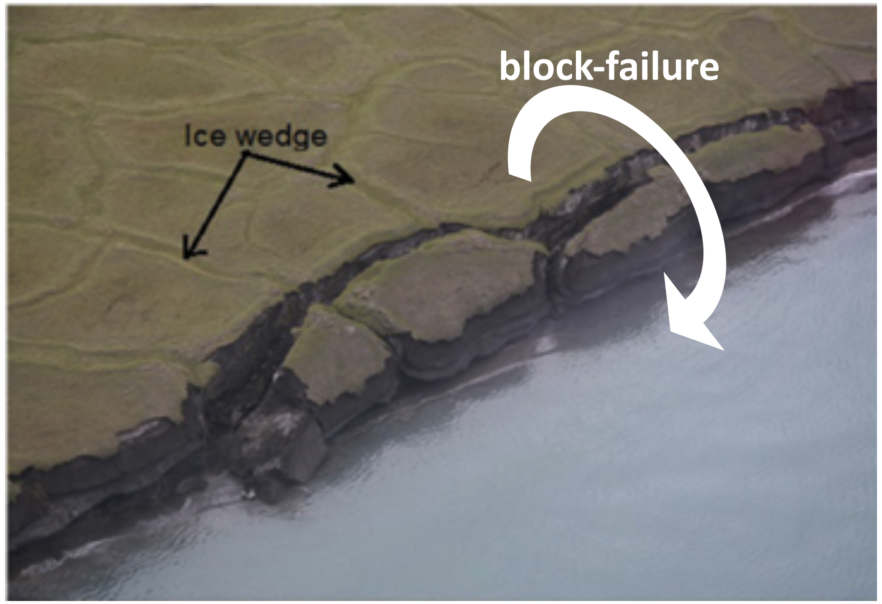

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There is a scale gap

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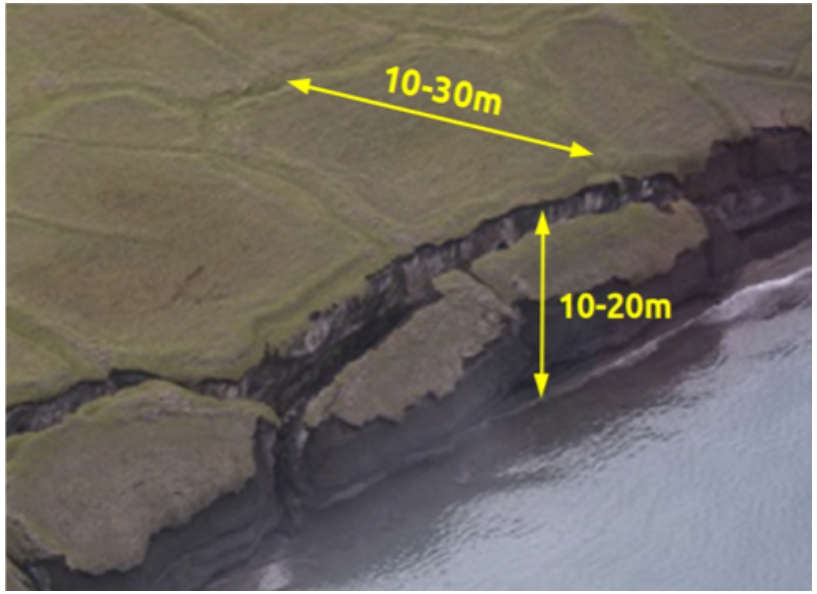

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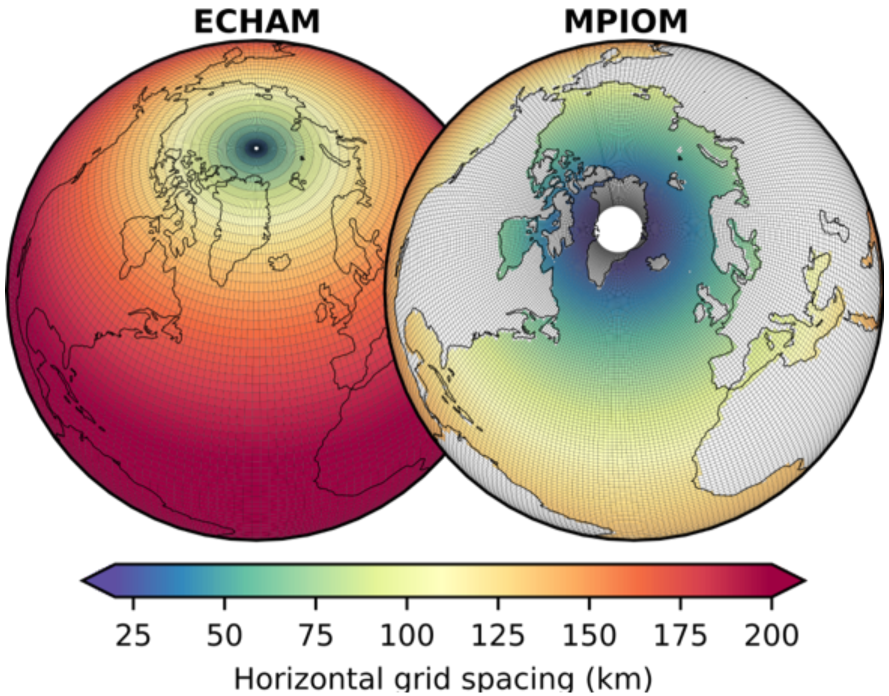

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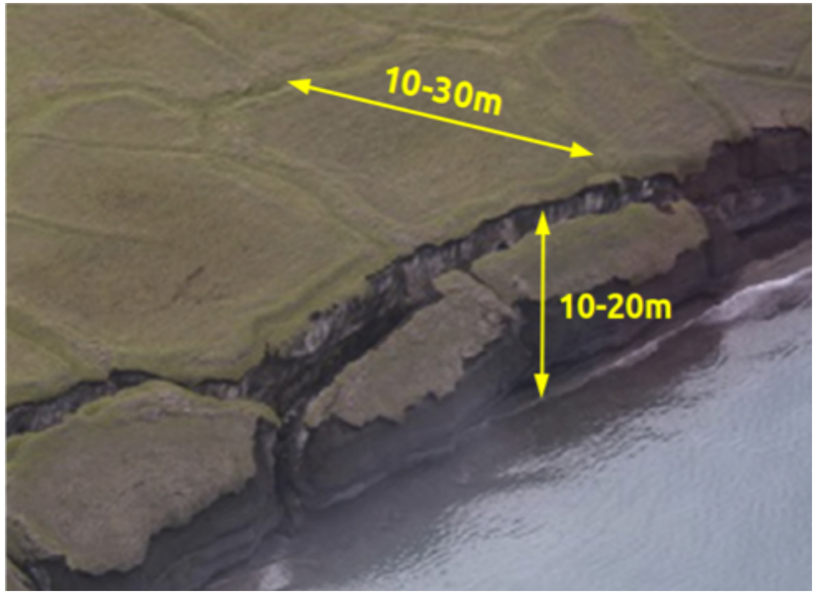

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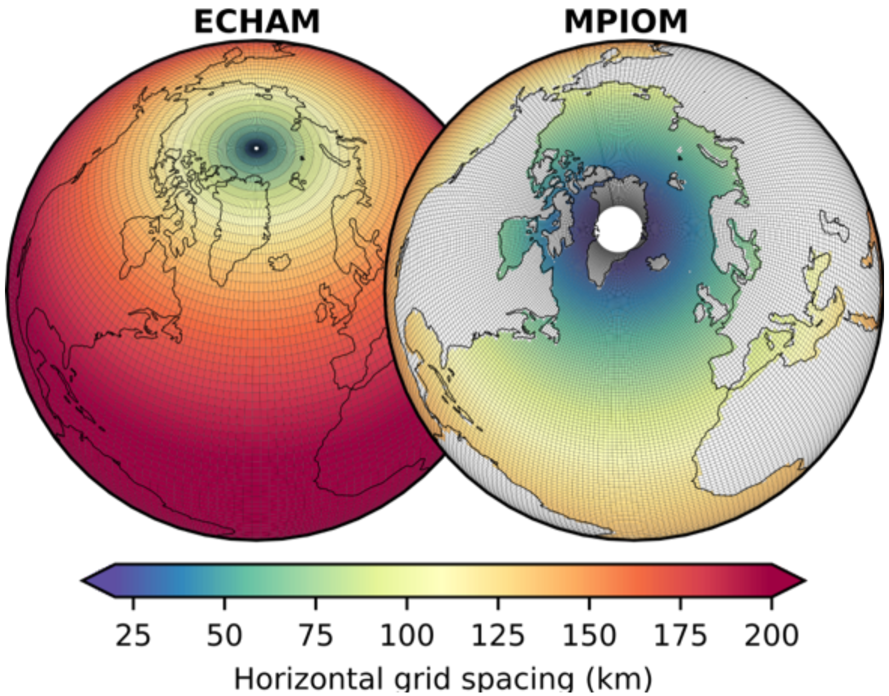

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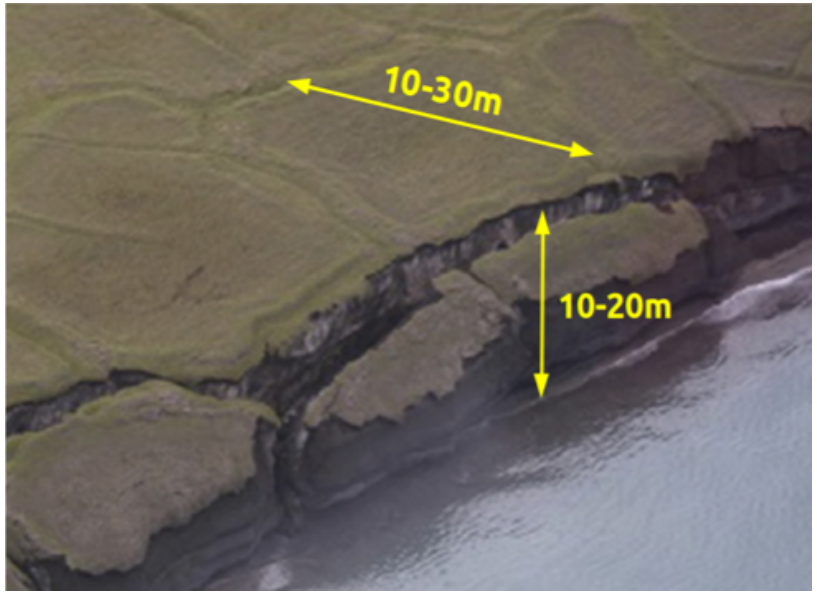

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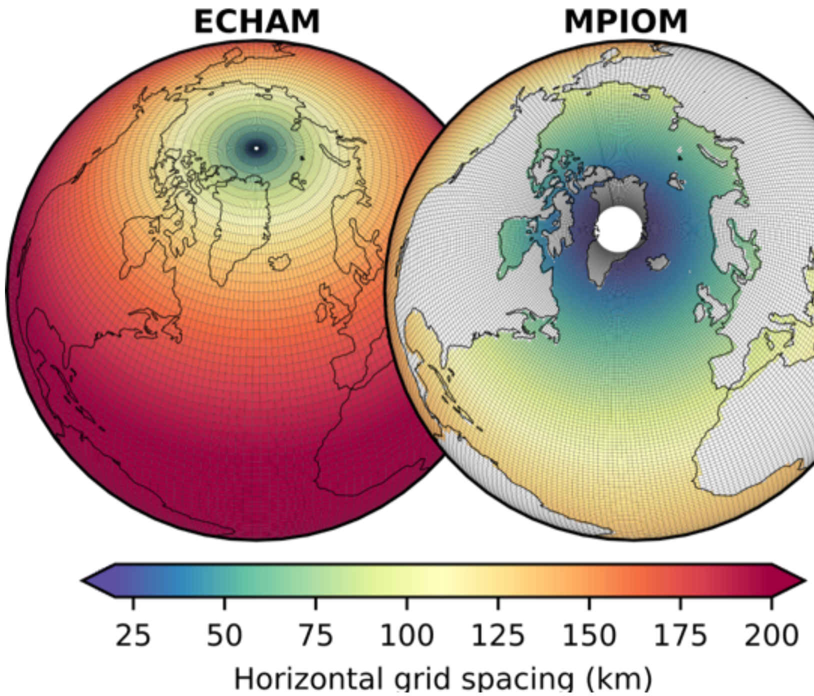
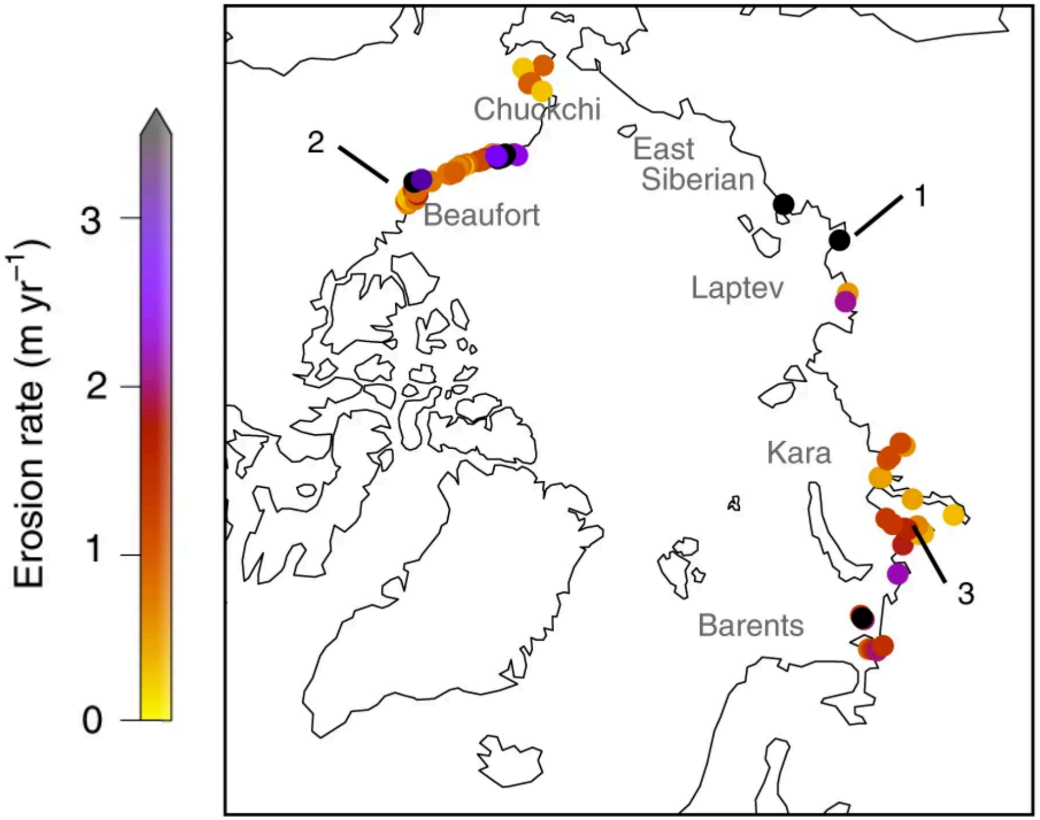


- Existing erosion models are **not compatible with ESMs** used for climate projections (e.g. CMIP6)
- Future projections of **permafrost-carbon loss** could be largely underestimated
- **New modelling frameworks are needed to close the scale gap**

Turetsky et al. (2019, 2020), Fritz et al. (2017)

A simple, semi-empirical model for Arctic coastal erosion

Observations from the Arctic Coastal Dynamics (ACD) database (Lantuit et al. 2012)



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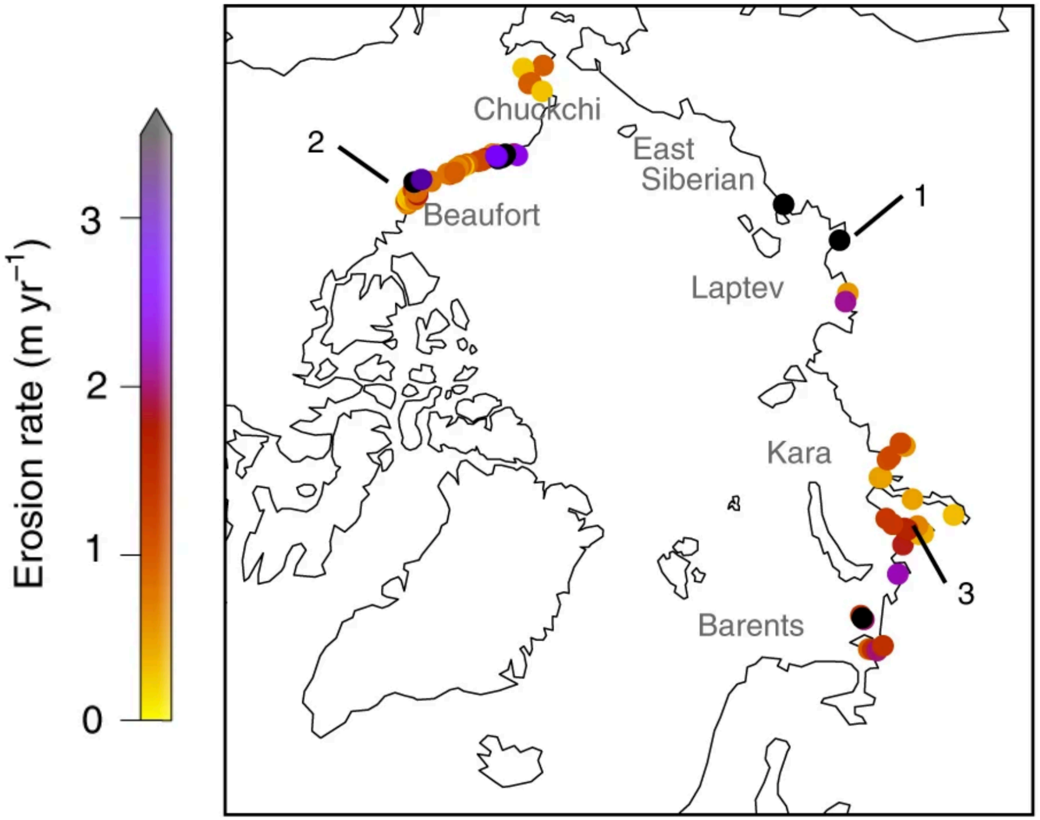

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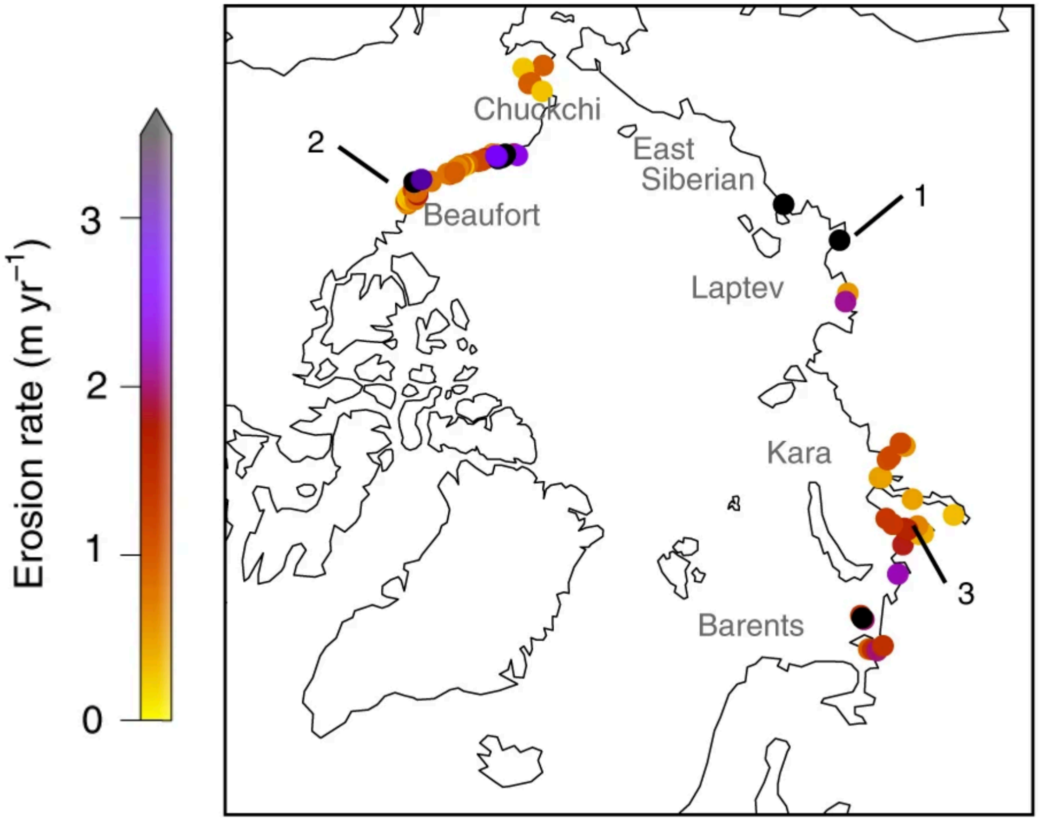

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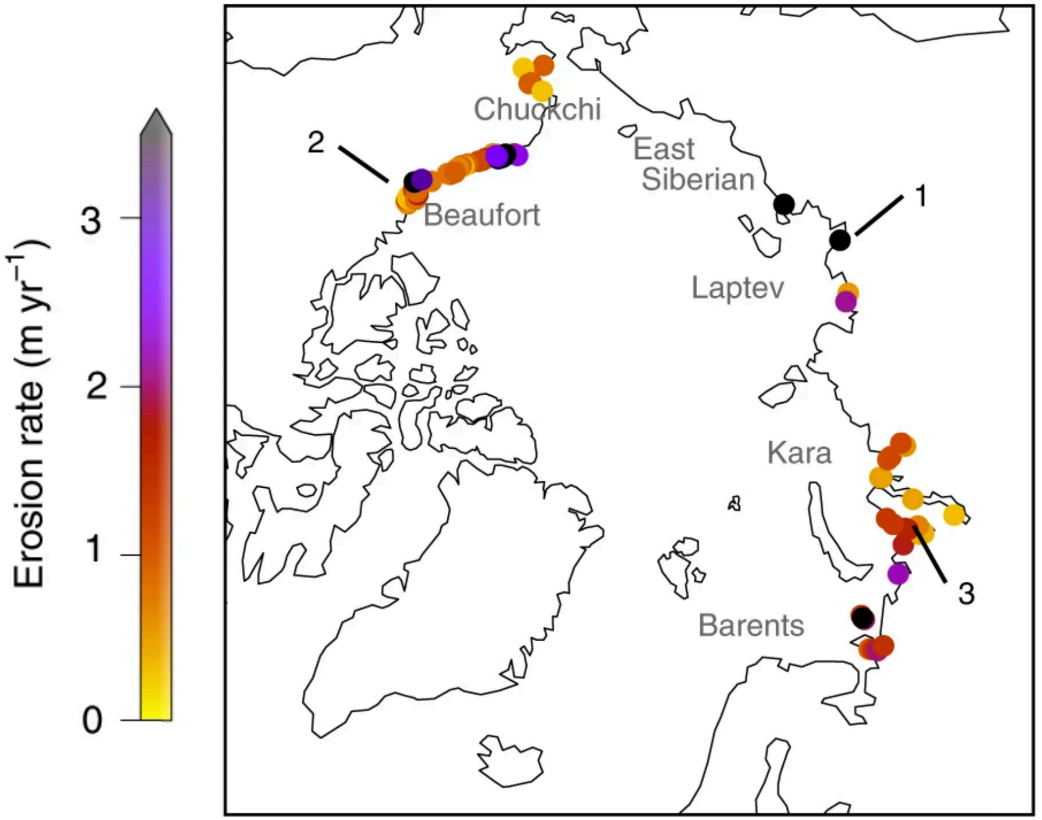

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Local daily-accumulated yearly:

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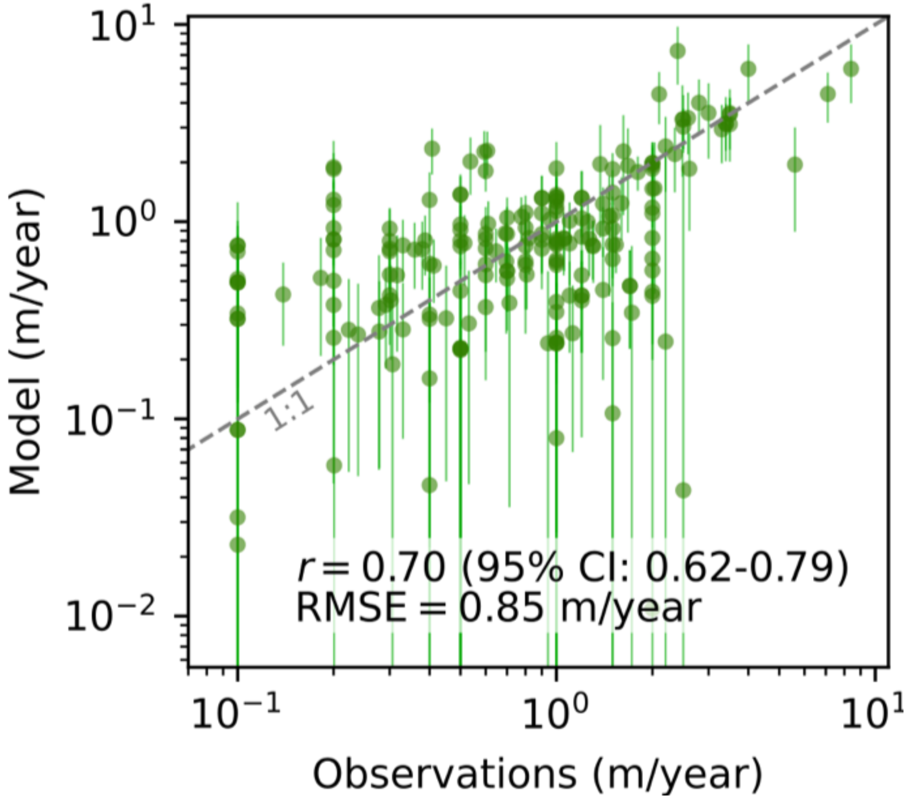
- Positive surface air temperature
- Ground-ice content

Pan-Arctic spatial variability

Ground-ice content, surface temperature and ocean waves explain **about 50%** of the spatial variability of long-term mean erosion rates



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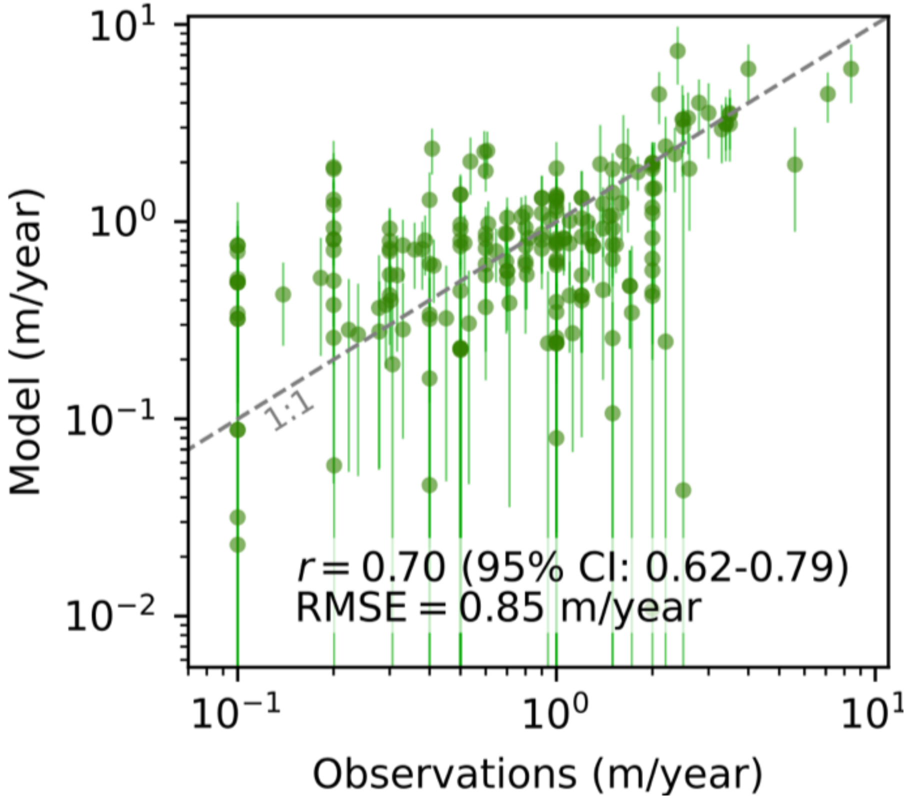
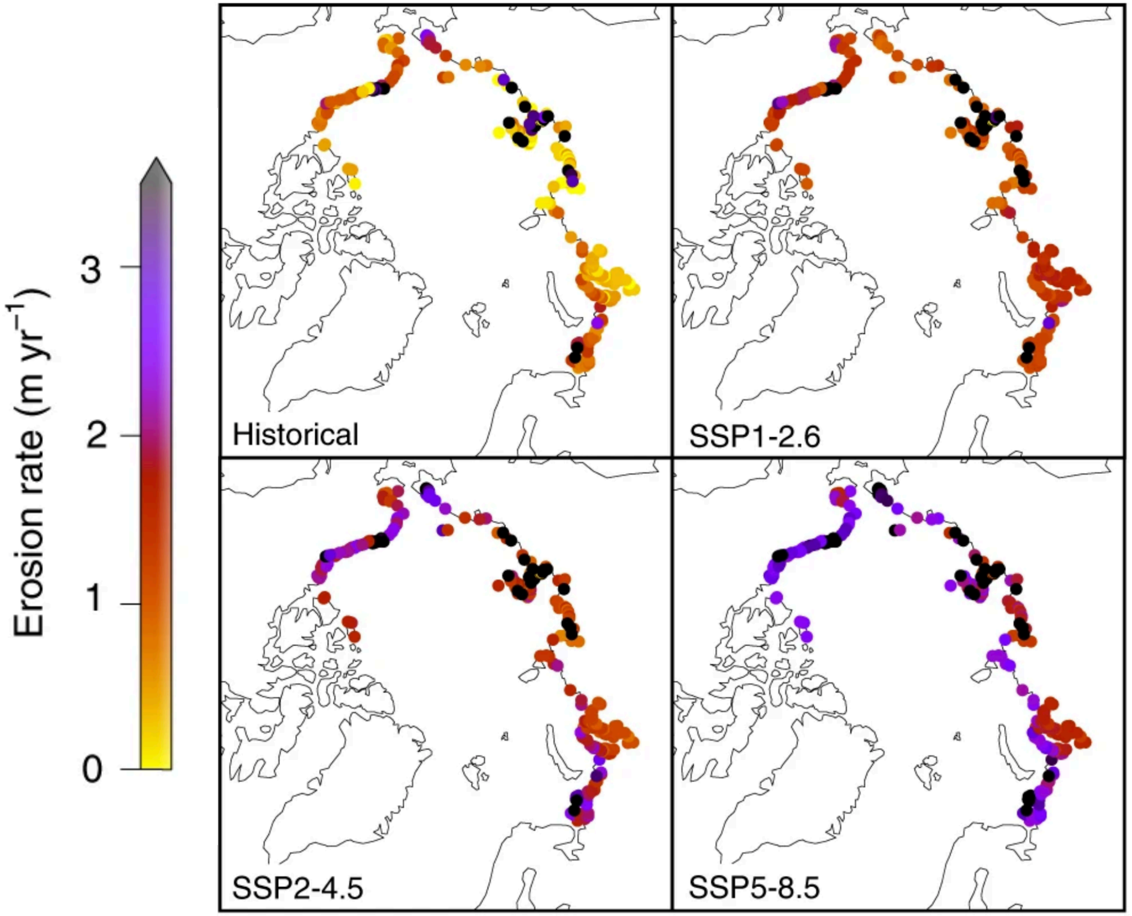


Future projections



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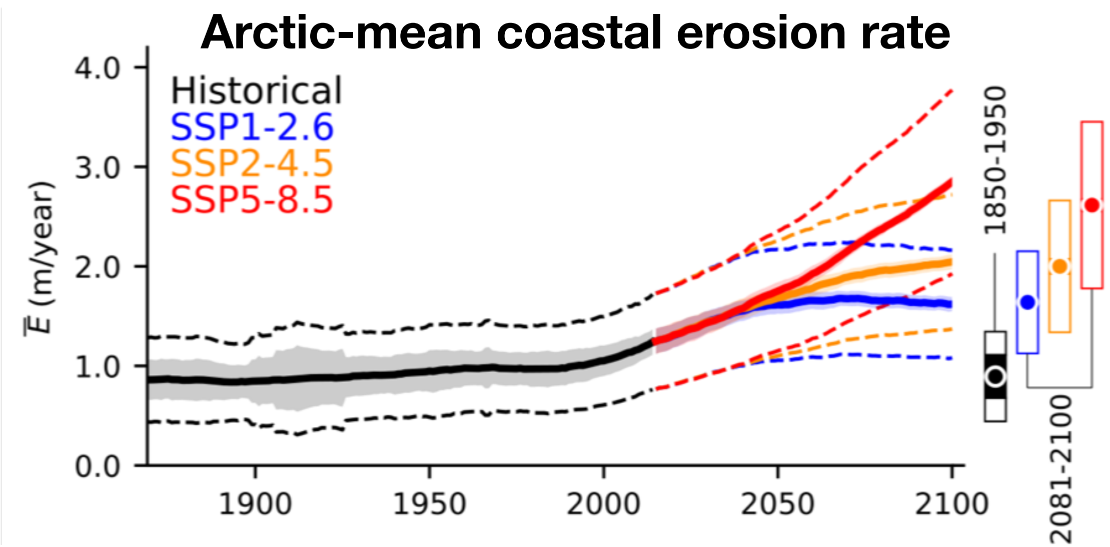
Historical and 21st-century projections



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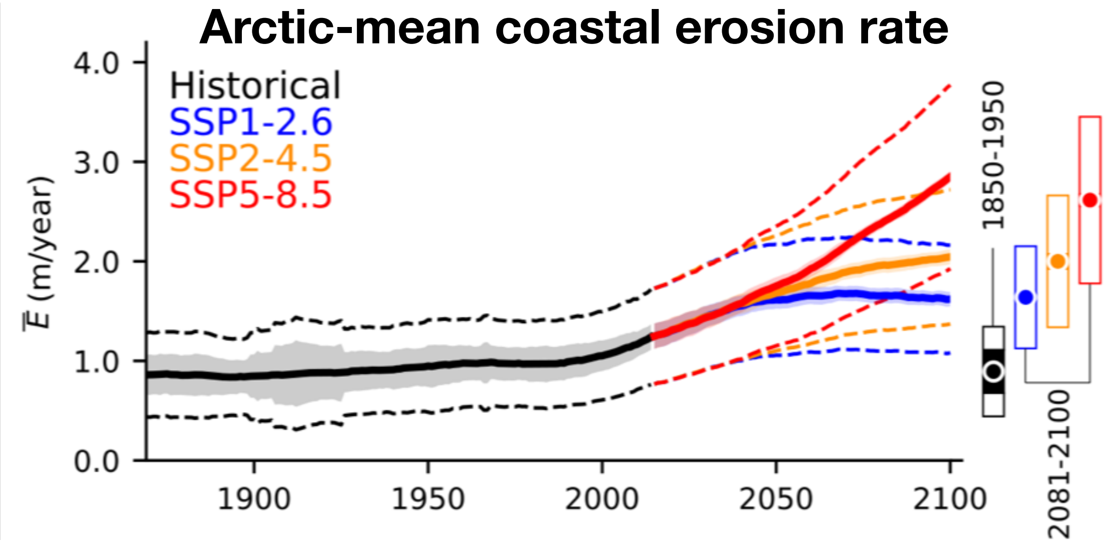

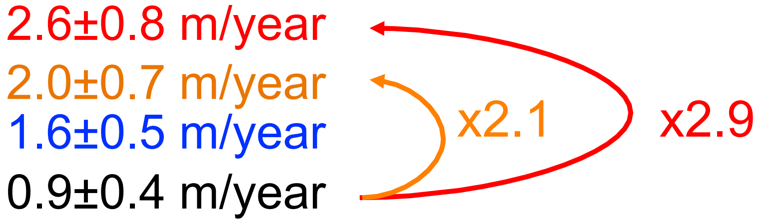

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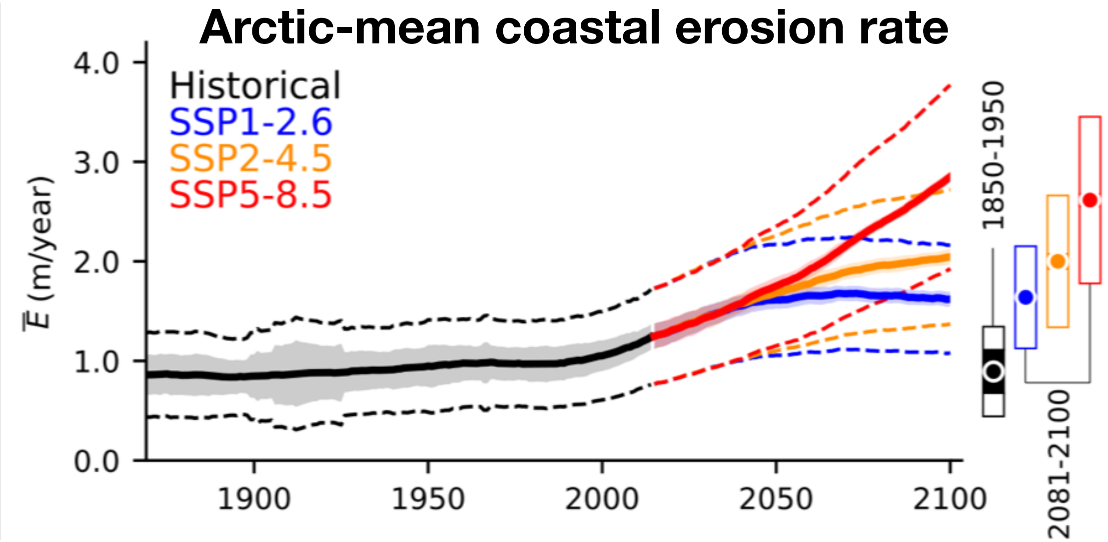

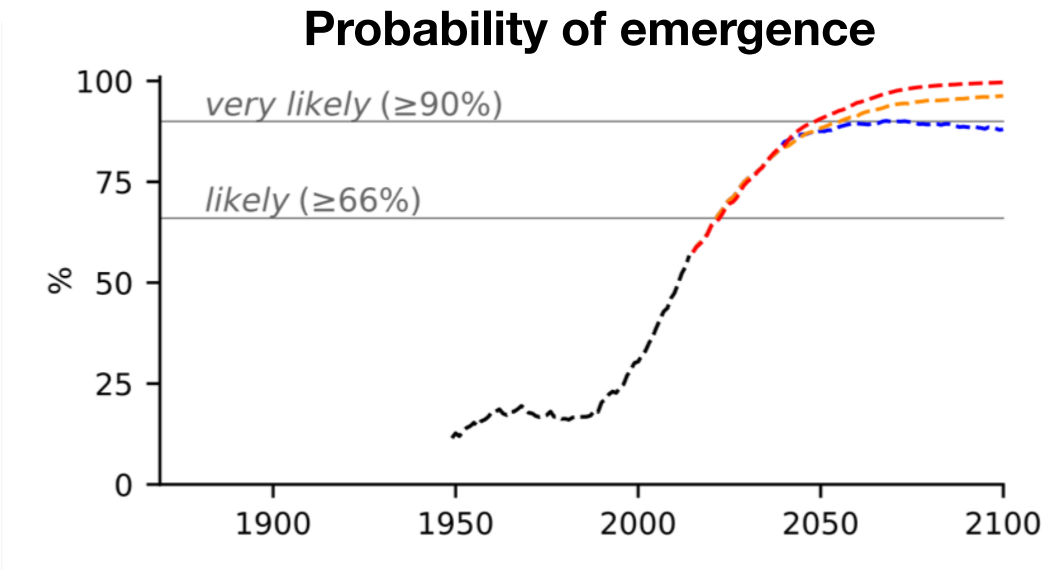

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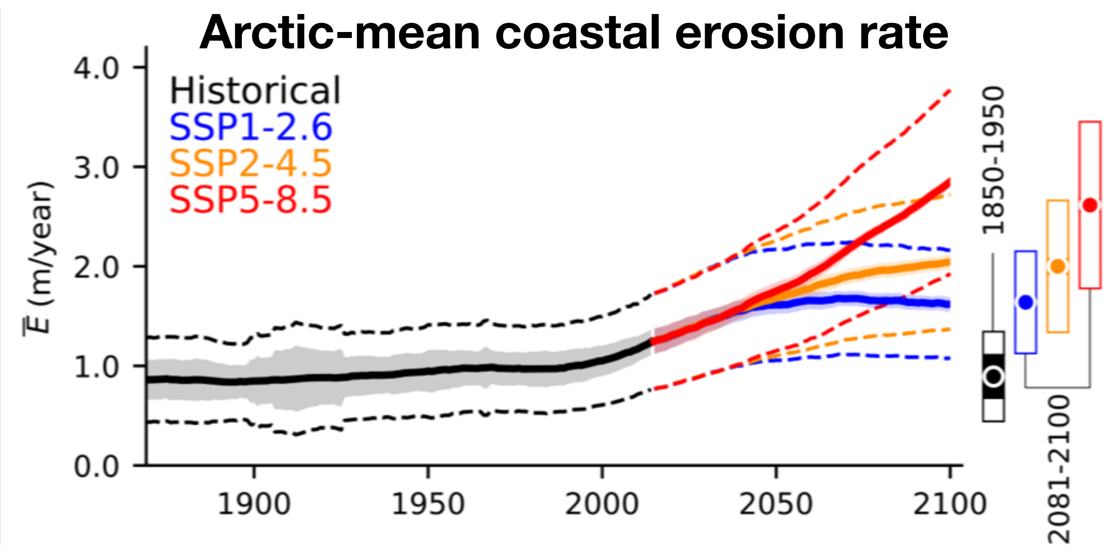

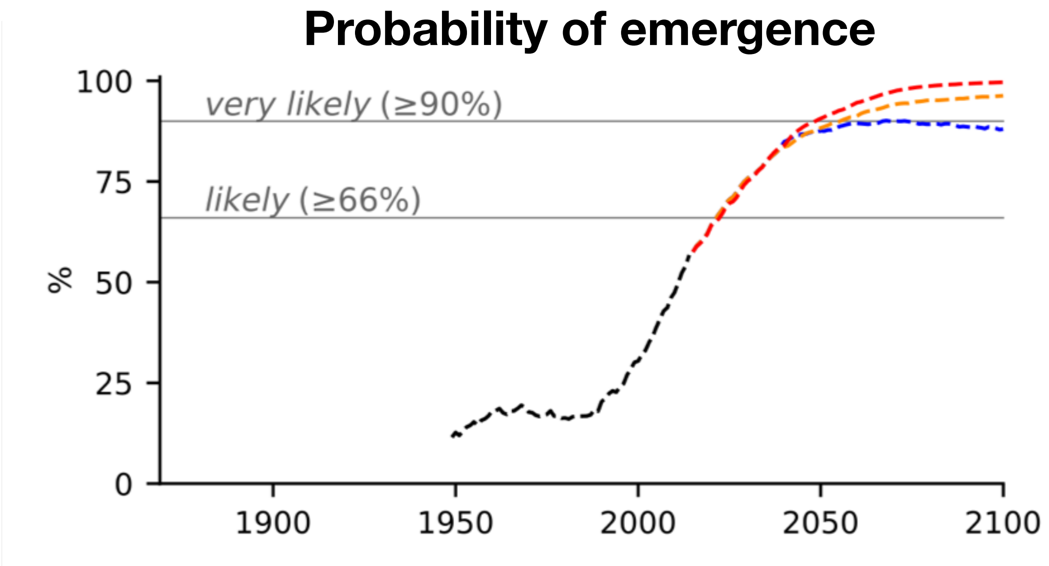

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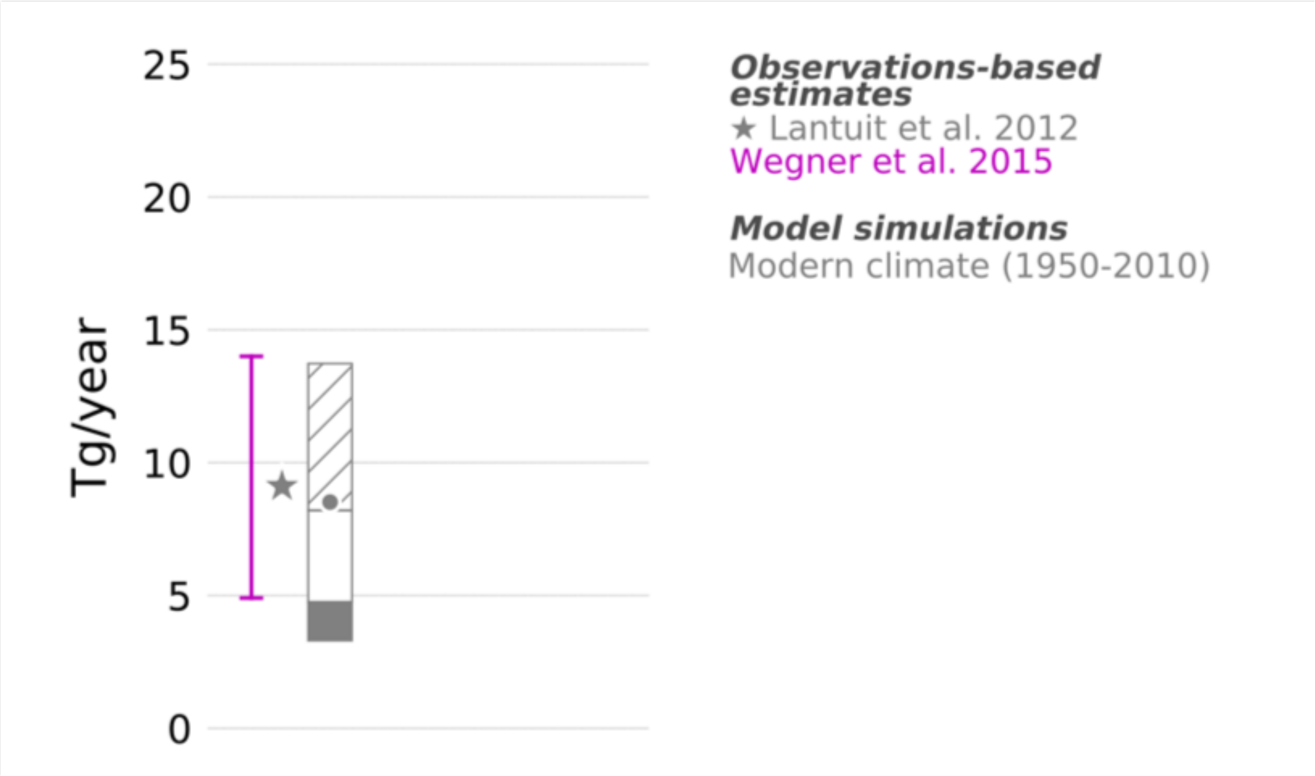
- Sensitivity to global-mean surface air temperature (GMST) about 0.4 (m/year)/°C (SSP2-4.5)

Nielsen et al. (2022, *Nature Climate Change*)

Permafrost organic carbon loss

Yearly loss due to coastal erosion



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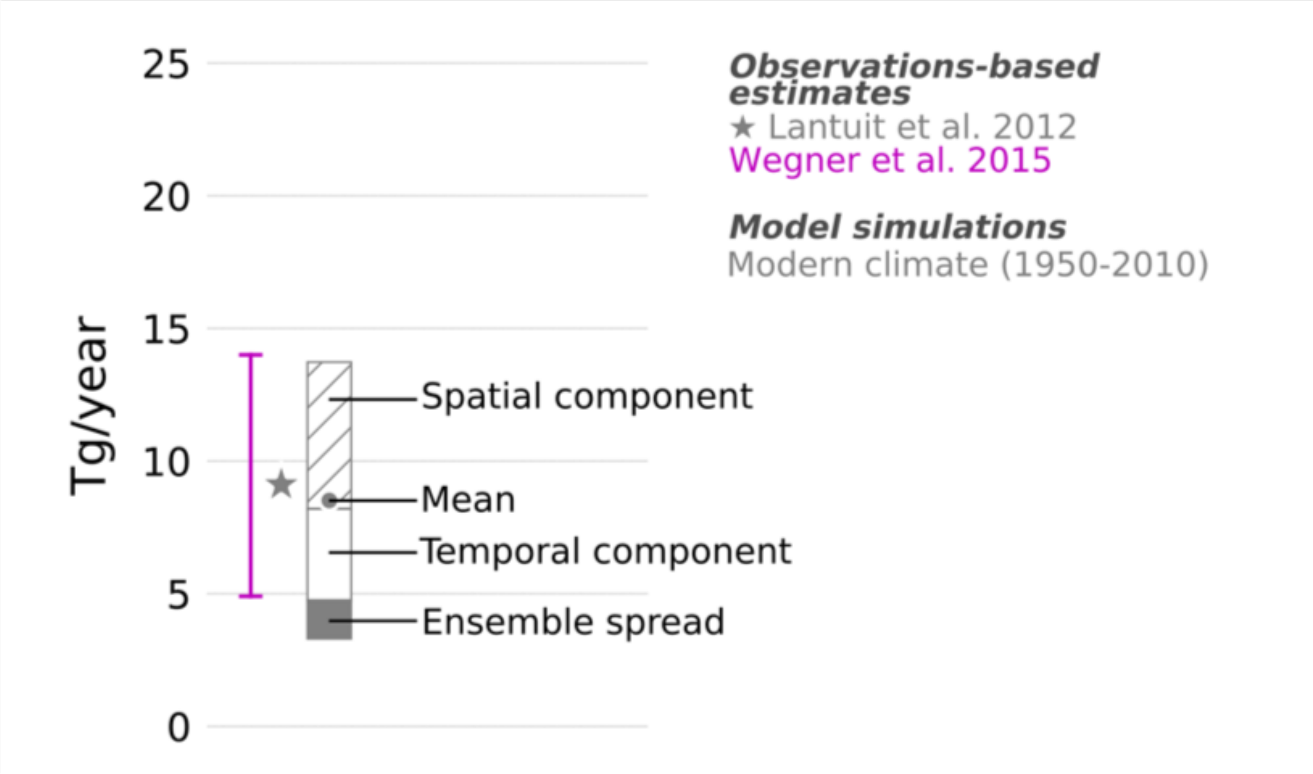

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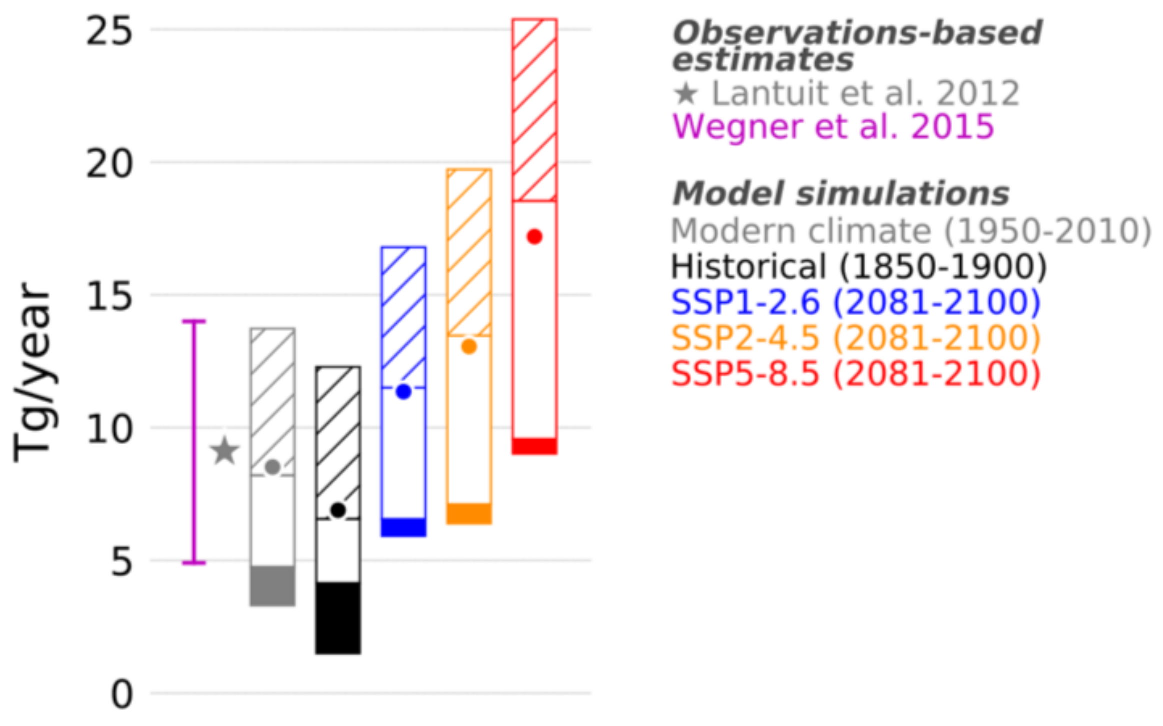

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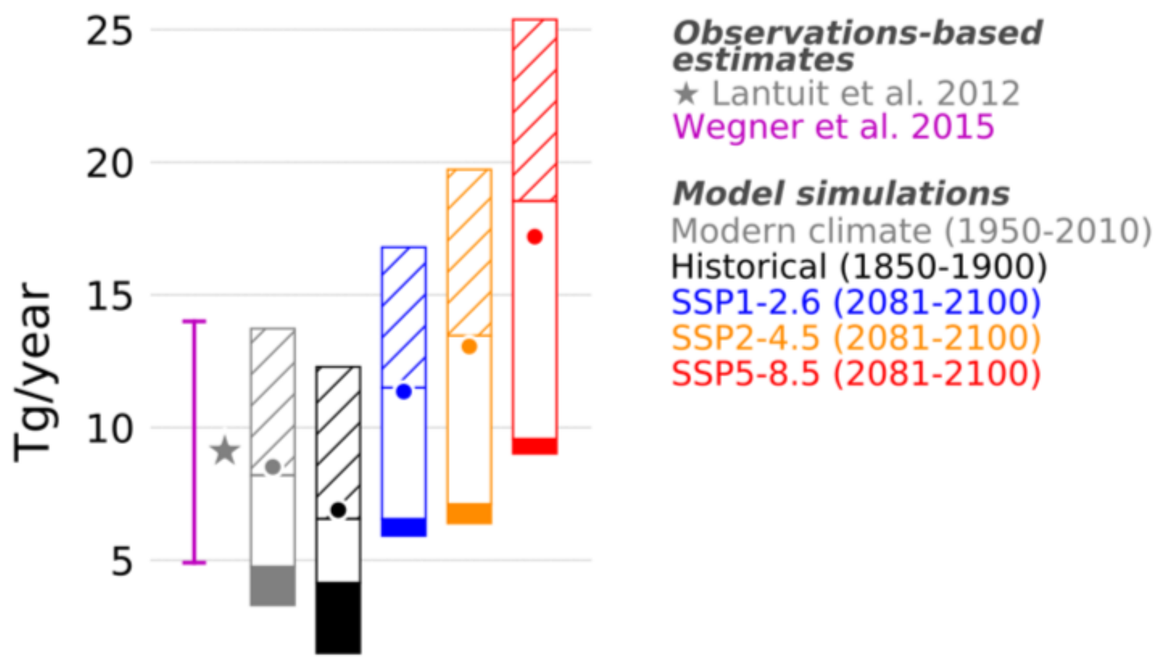
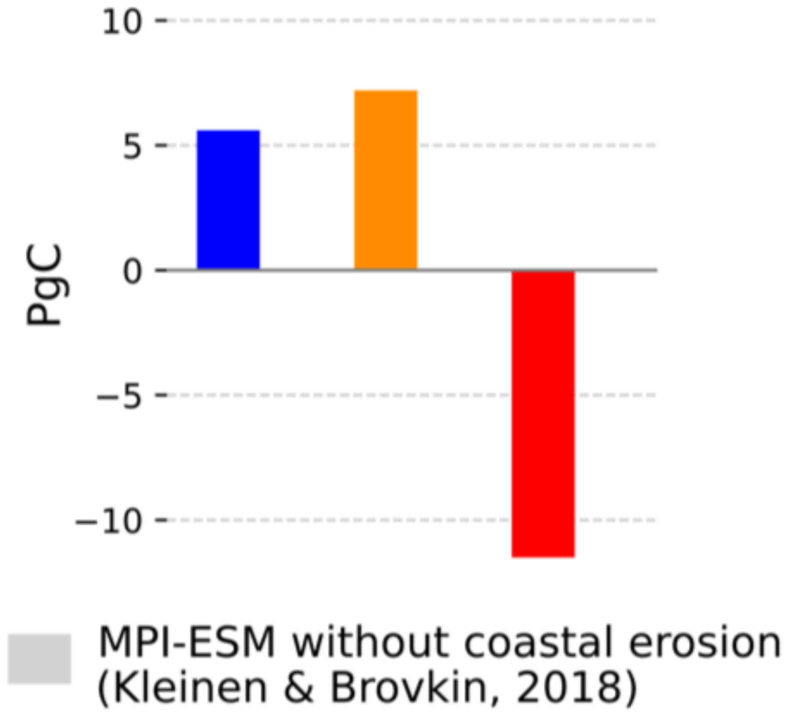


Net cumulative change of permafrost carbon (1900-2100)



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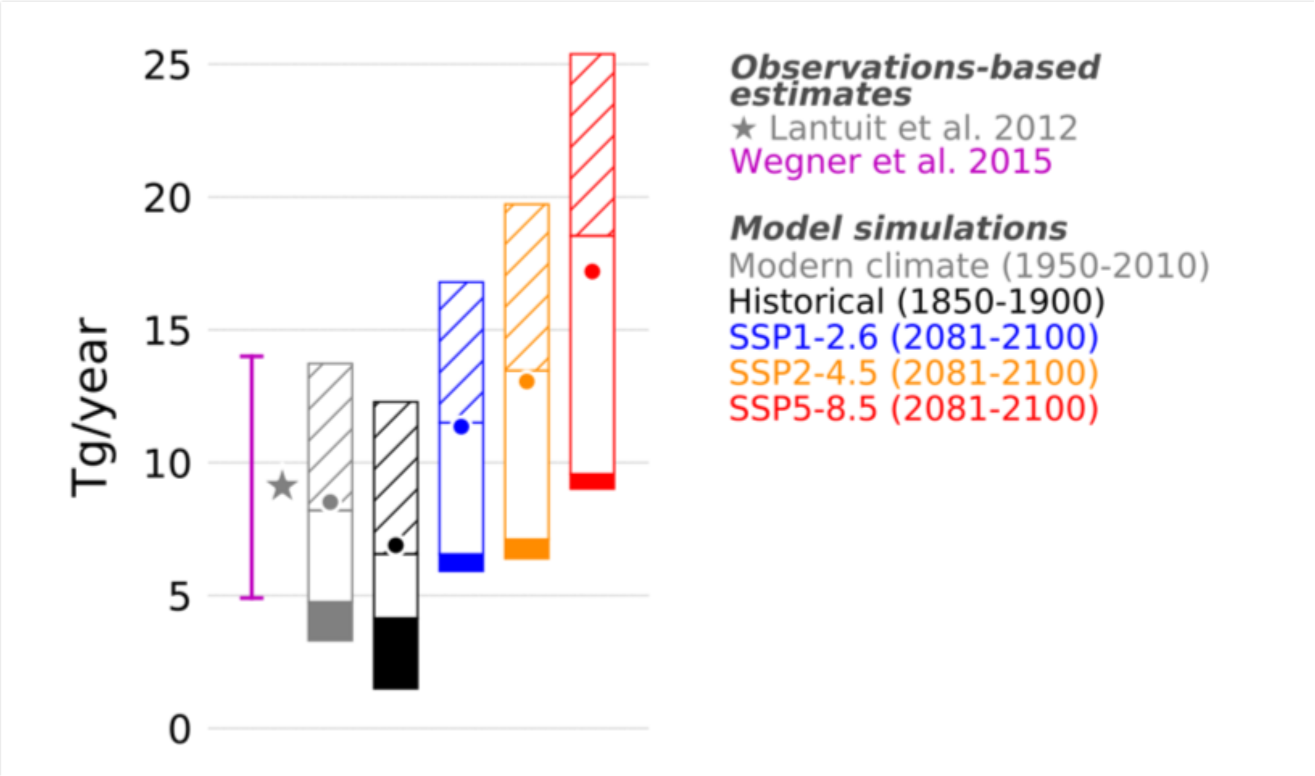

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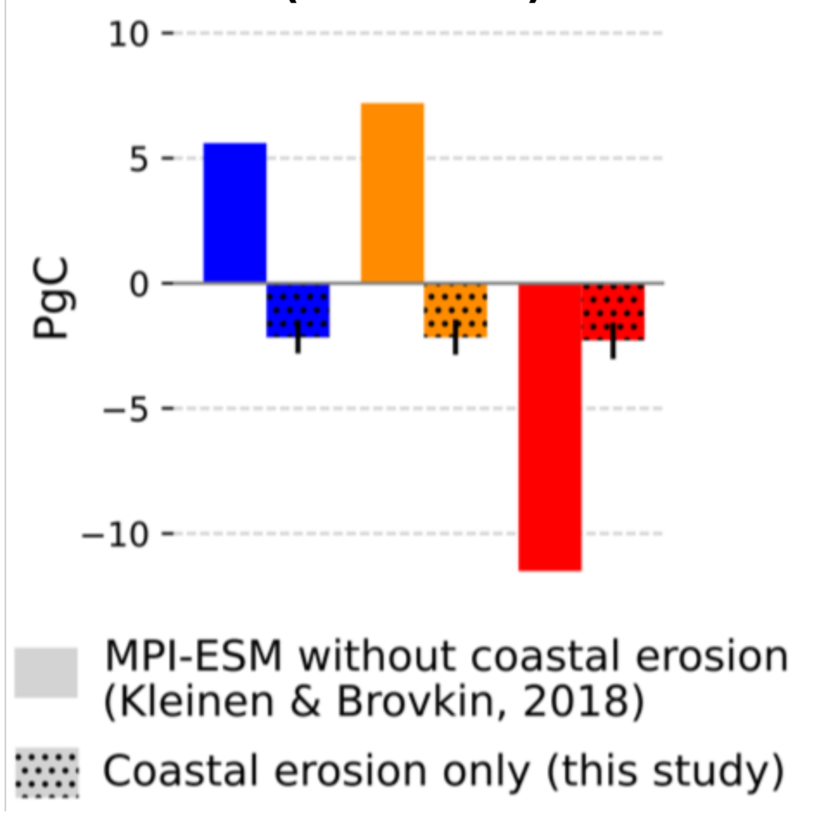

- Most uncertainties originate in the erosion model
- Coastal erosion accelerates permafrost carbon loss in all scenarios

Nielsen et al. (2022, *Nature Climate Change*)


Organic Matter

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Tanski *et al.* (2019, 2020)

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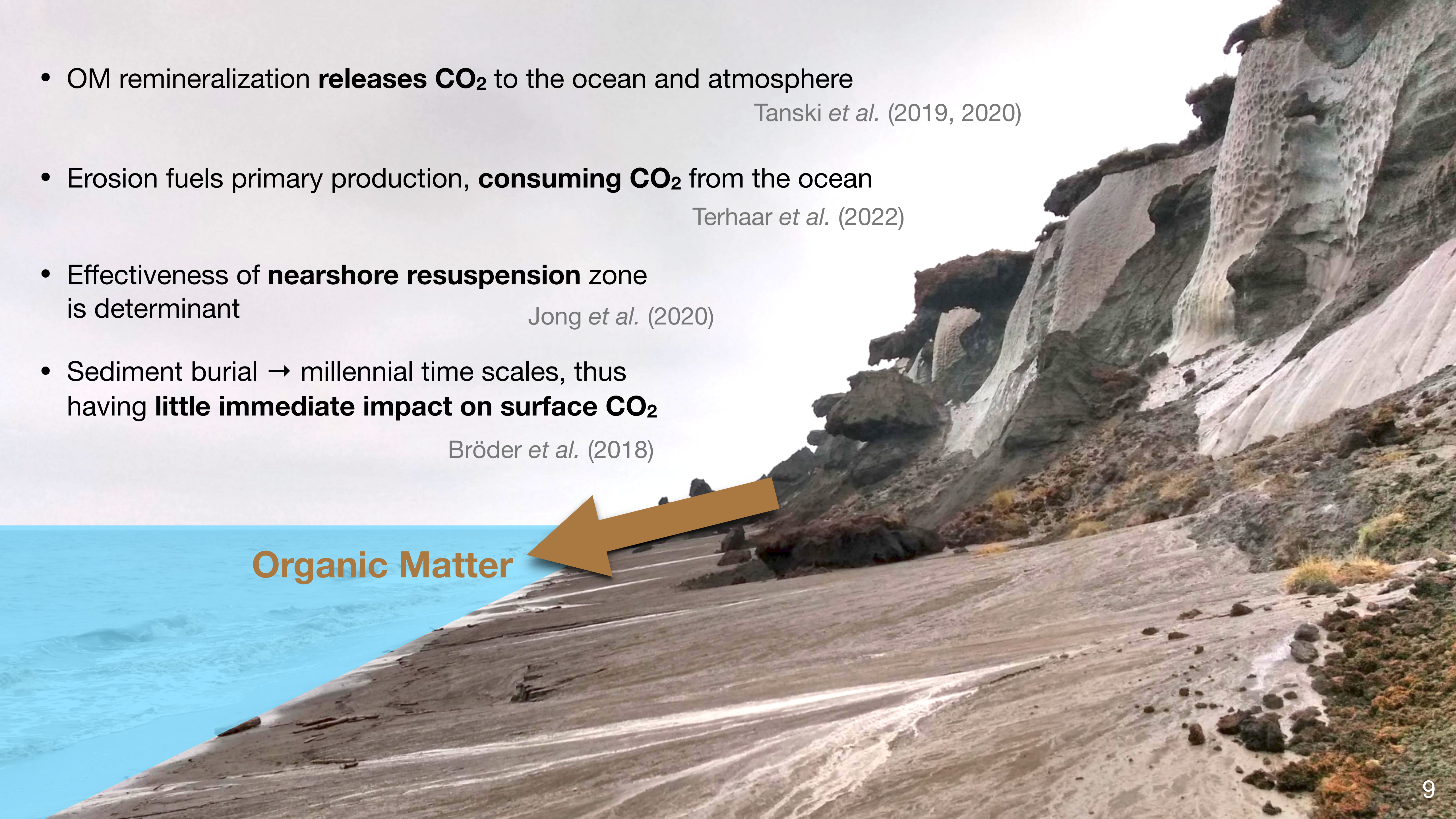

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What is the impact of increasing permafrost erosion on the Arctic Ocean's CO_2 uptake from the atmosphere?

Permafrost Organic Matter (OM) in MPI-ESM

Limitations

- Lack of specific **tracers for permafrost OM**, with different C/N ratios and remineralization rates
- Lack of **resuspension** driven by tides surface waves in the nearshore zone

Nielsen *et al.* (in prep.)

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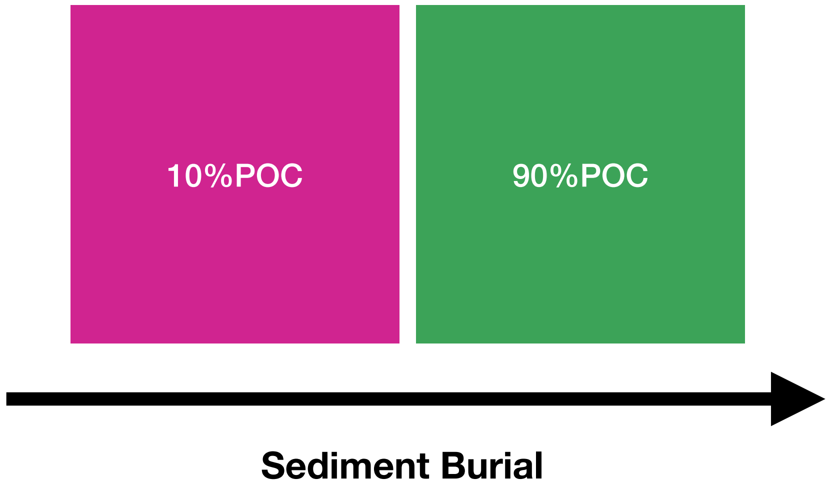

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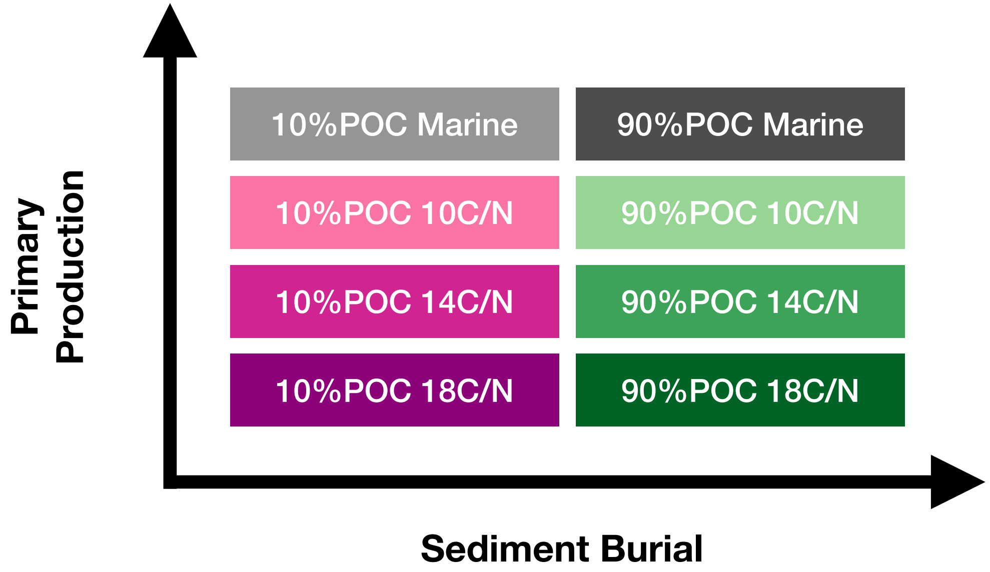

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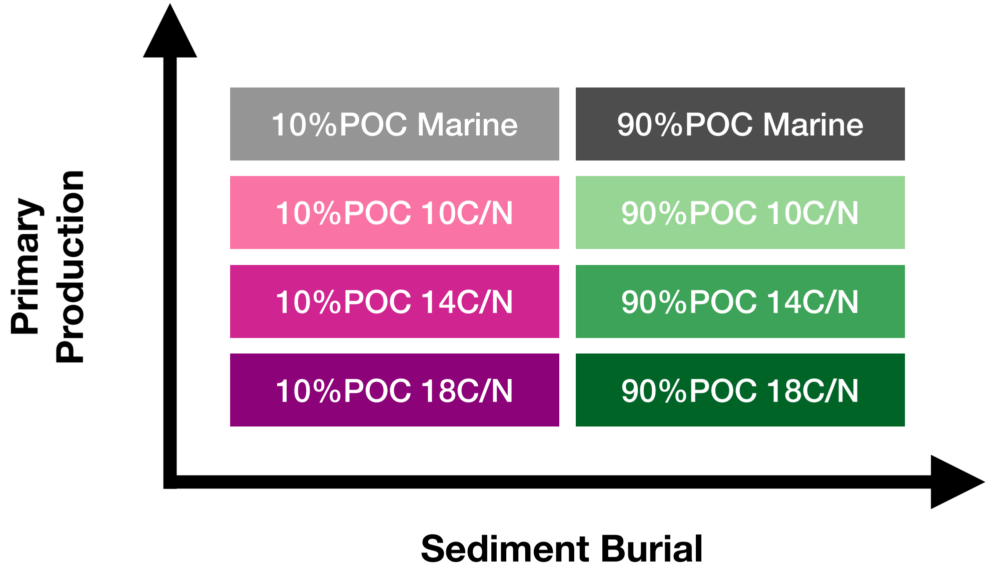

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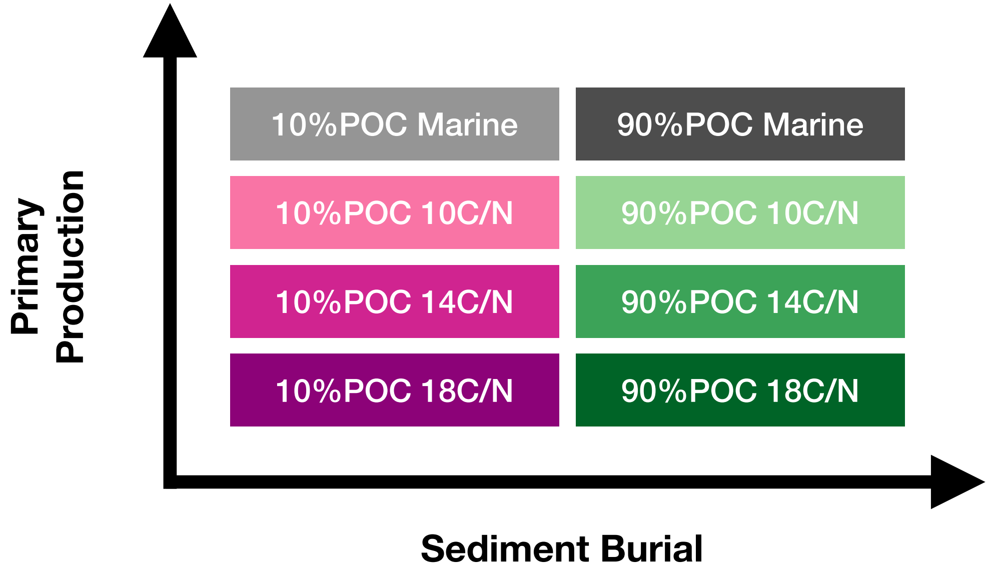
- 350 years of spin-up with historical erosion rates until stable surface Arctic Ocean
- Historical and Future scenarios until 2100 (CMIP6)



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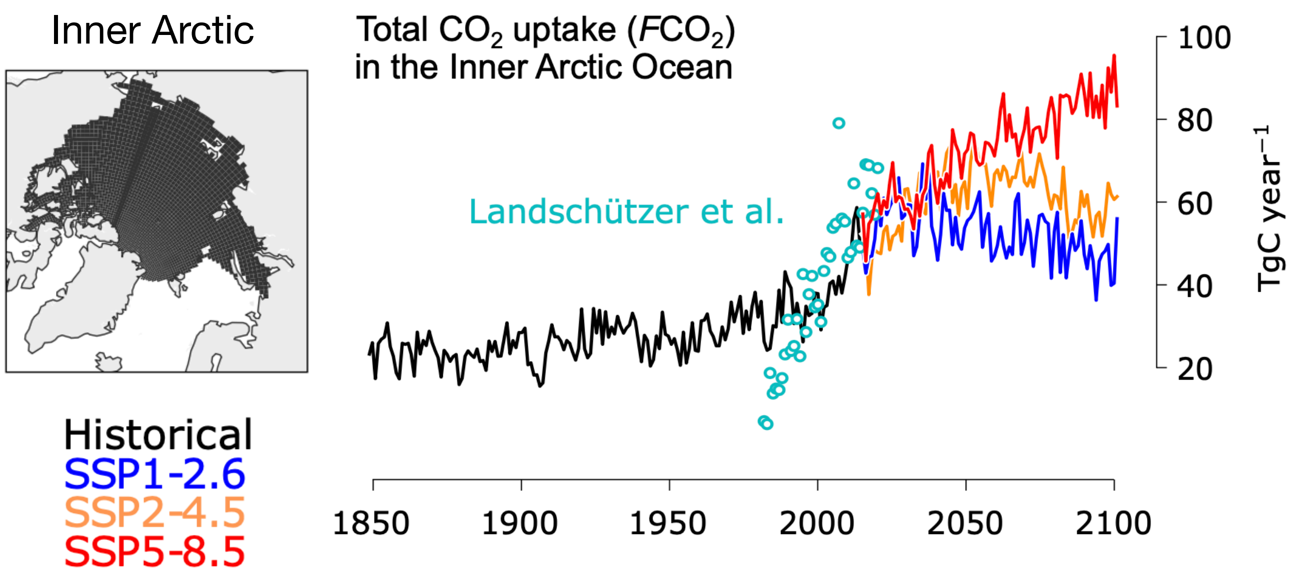
Arctic Ocean's CO_2 uptake



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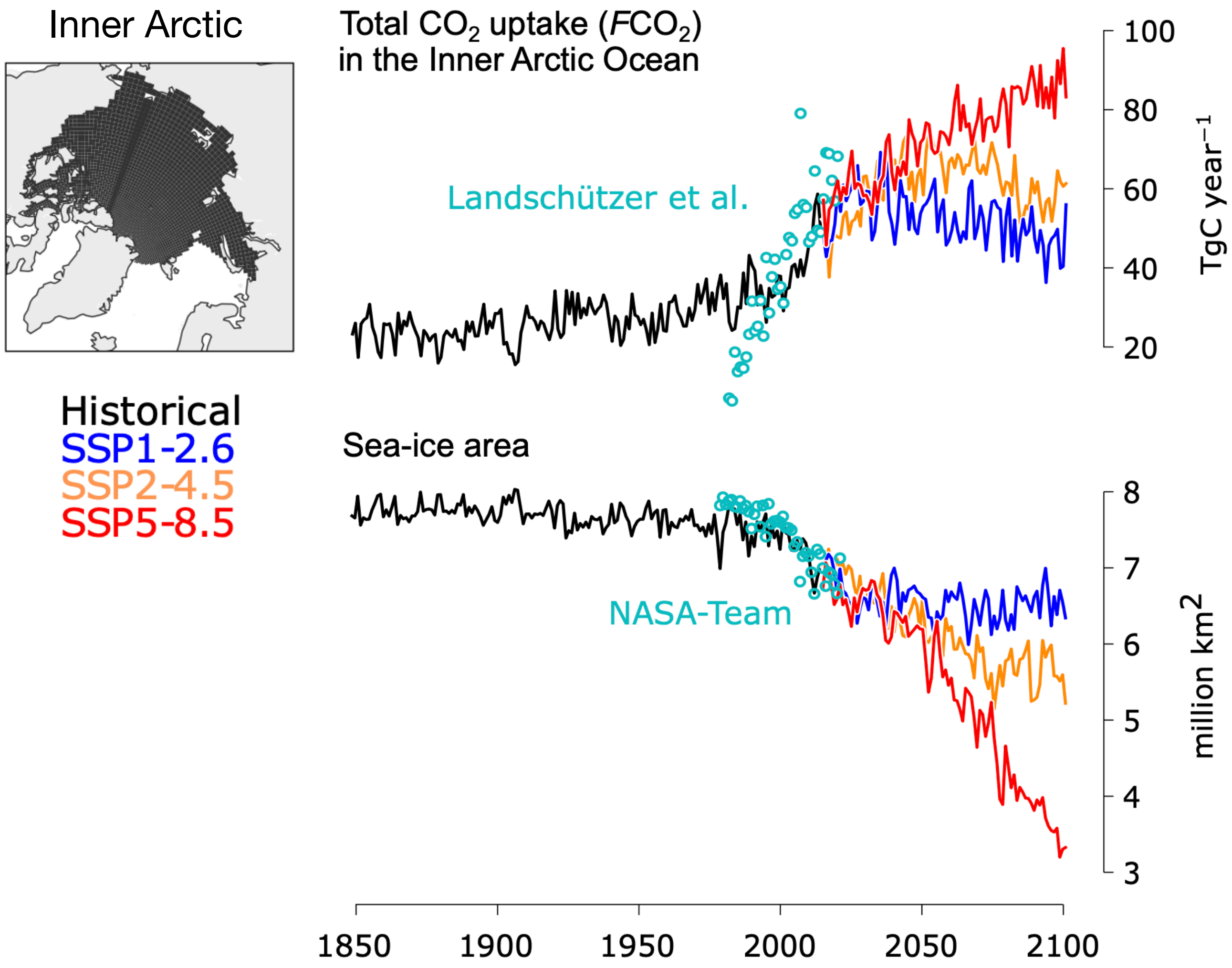

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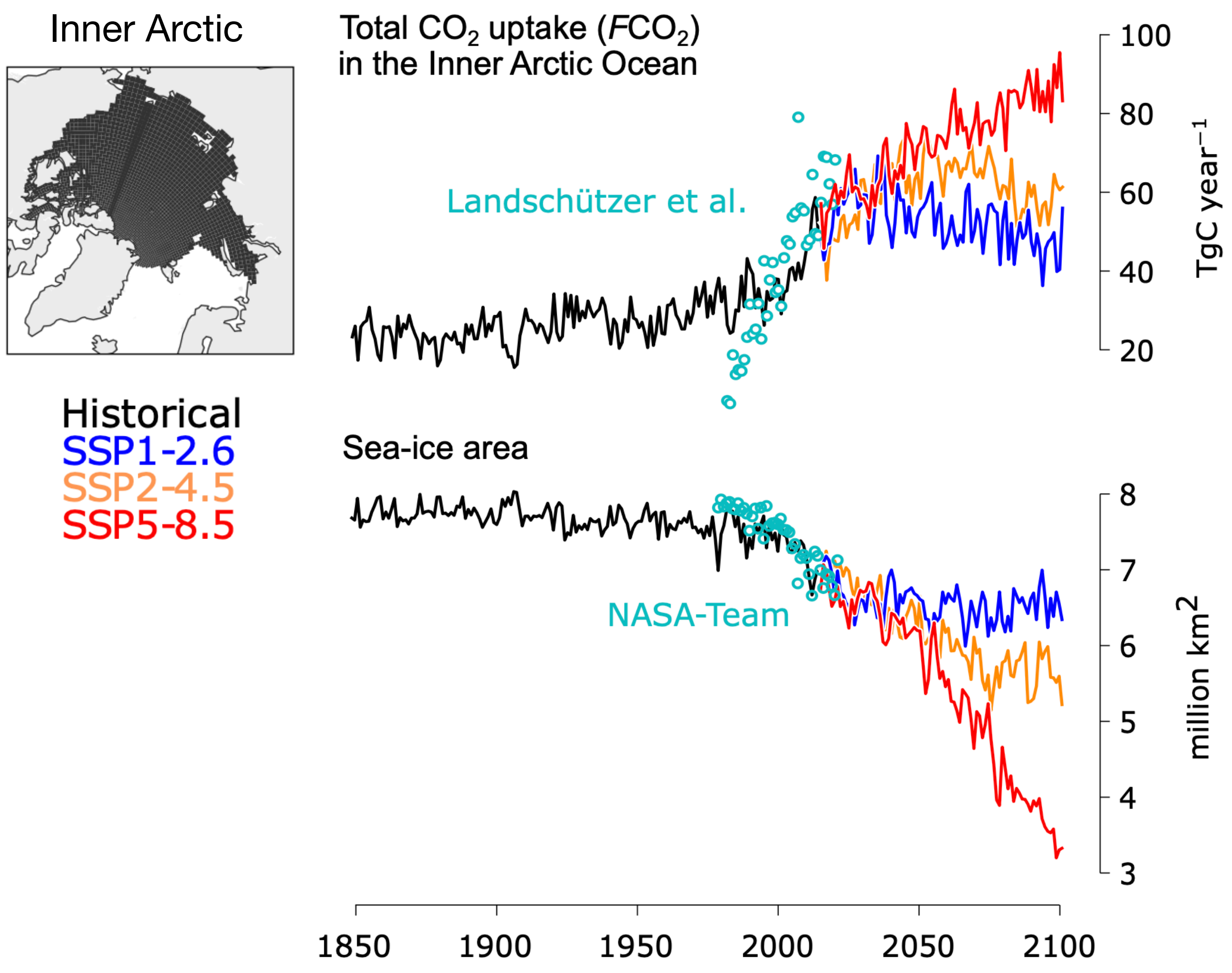
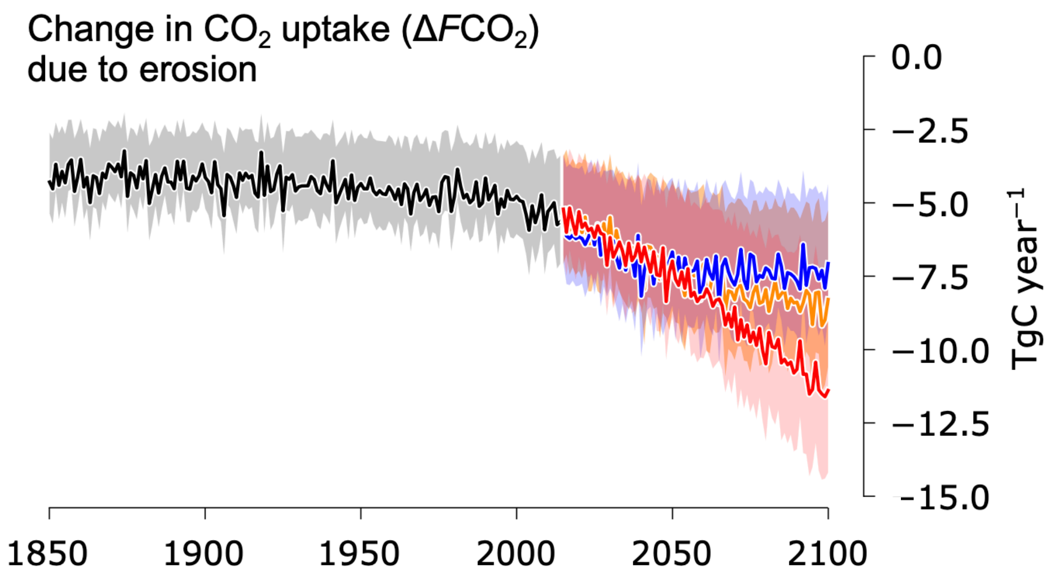
Arctic Ocean's CO_2 uptake decreases due to erosion





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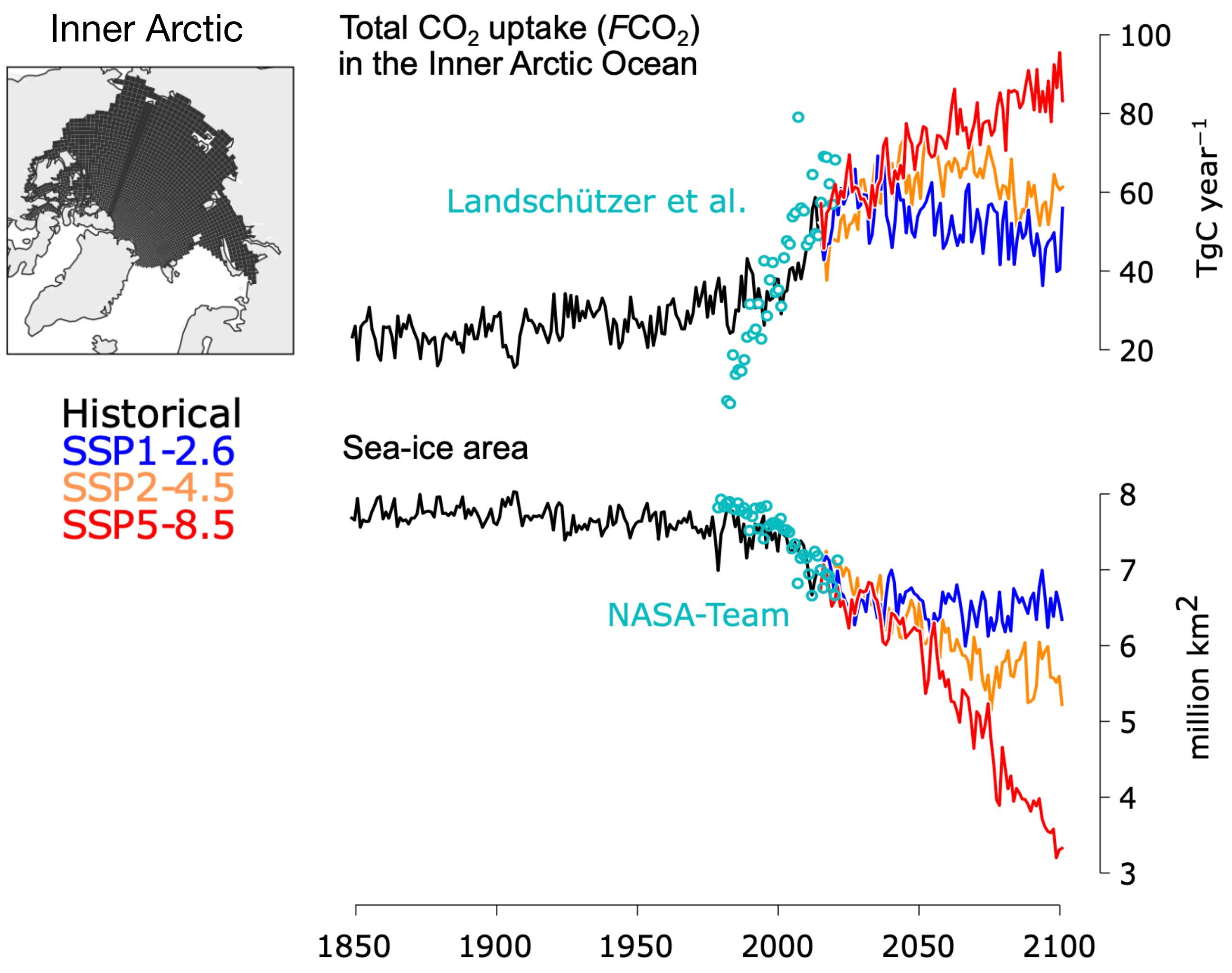
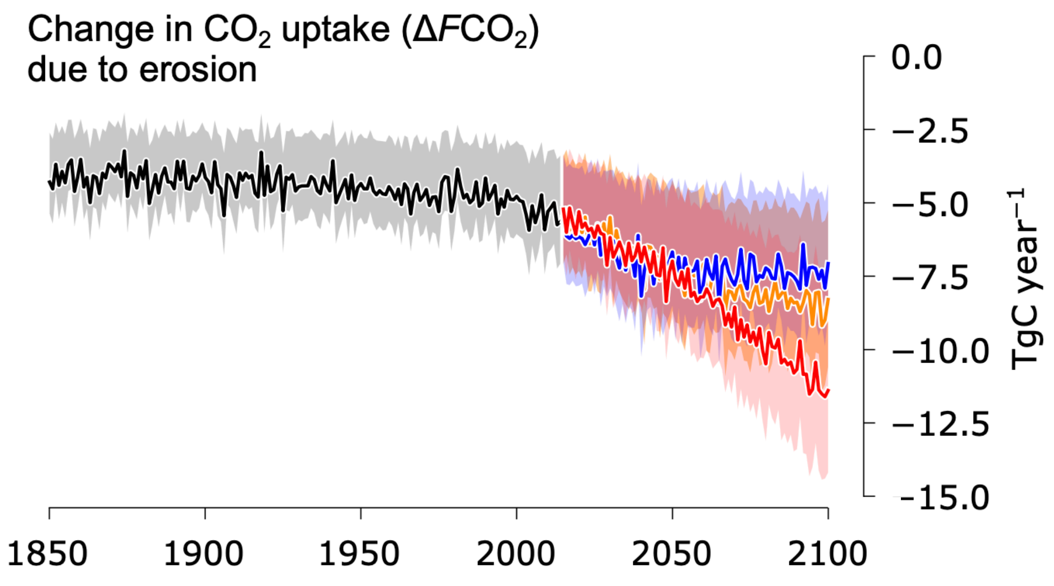


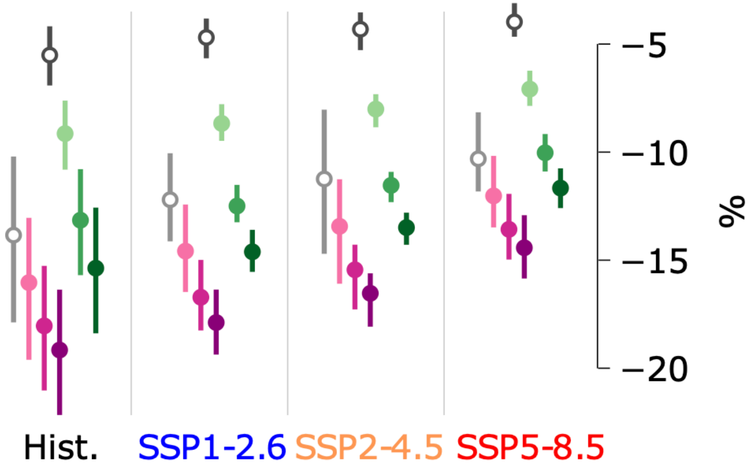


- Reduction of CO_2 uptake by about 5 to 14 TgC/year
- Model uncertainties are as large as scenario uncertainties

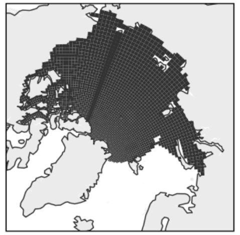
Nielsen *et al.* (in prep.)

Uncertainties originate in the OM representation

Percentage change of CO_2 uptake



Inner Arctic



15 (9 to 19) %
14 (8 to 18) %
13 (8 to 16) %
11 (7 to 14) %

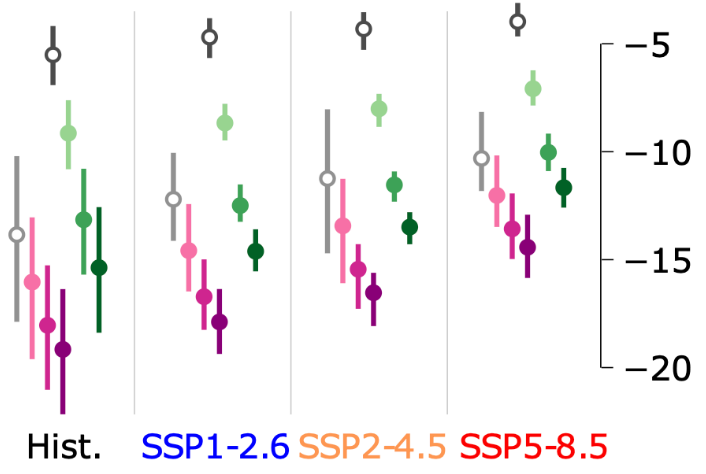
10%POC 10C/N
10%POC 14C/N
10%POC 18C/N

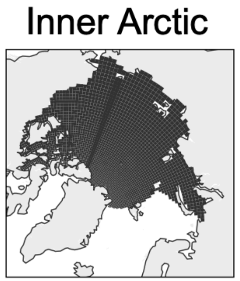
90%POC 10C/N
90%POC 14C/N
90%POC 18C/N

90%POC Marine
10%POC Marine

Uncertainties originate in the OM representation

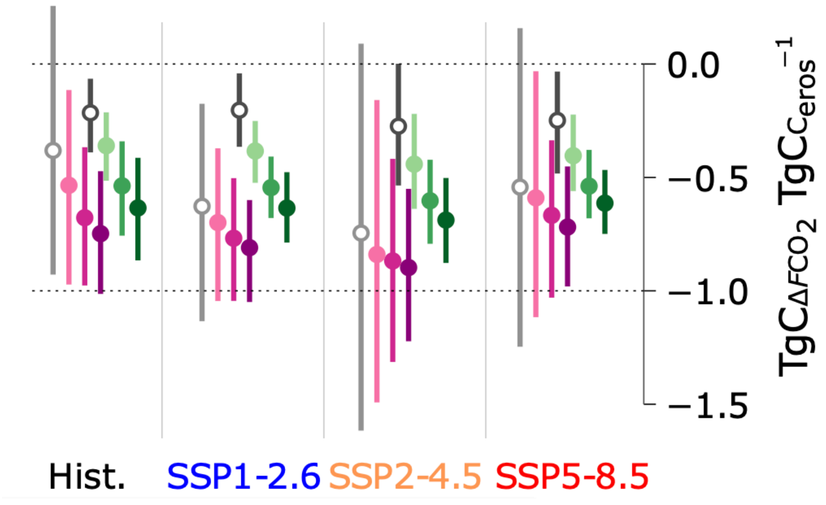
Percentage change of CO_2 uptake





15 (9 to 19) %
14 (8 to 18) %
13 (8 to 16) %
11 (7 to 14) %

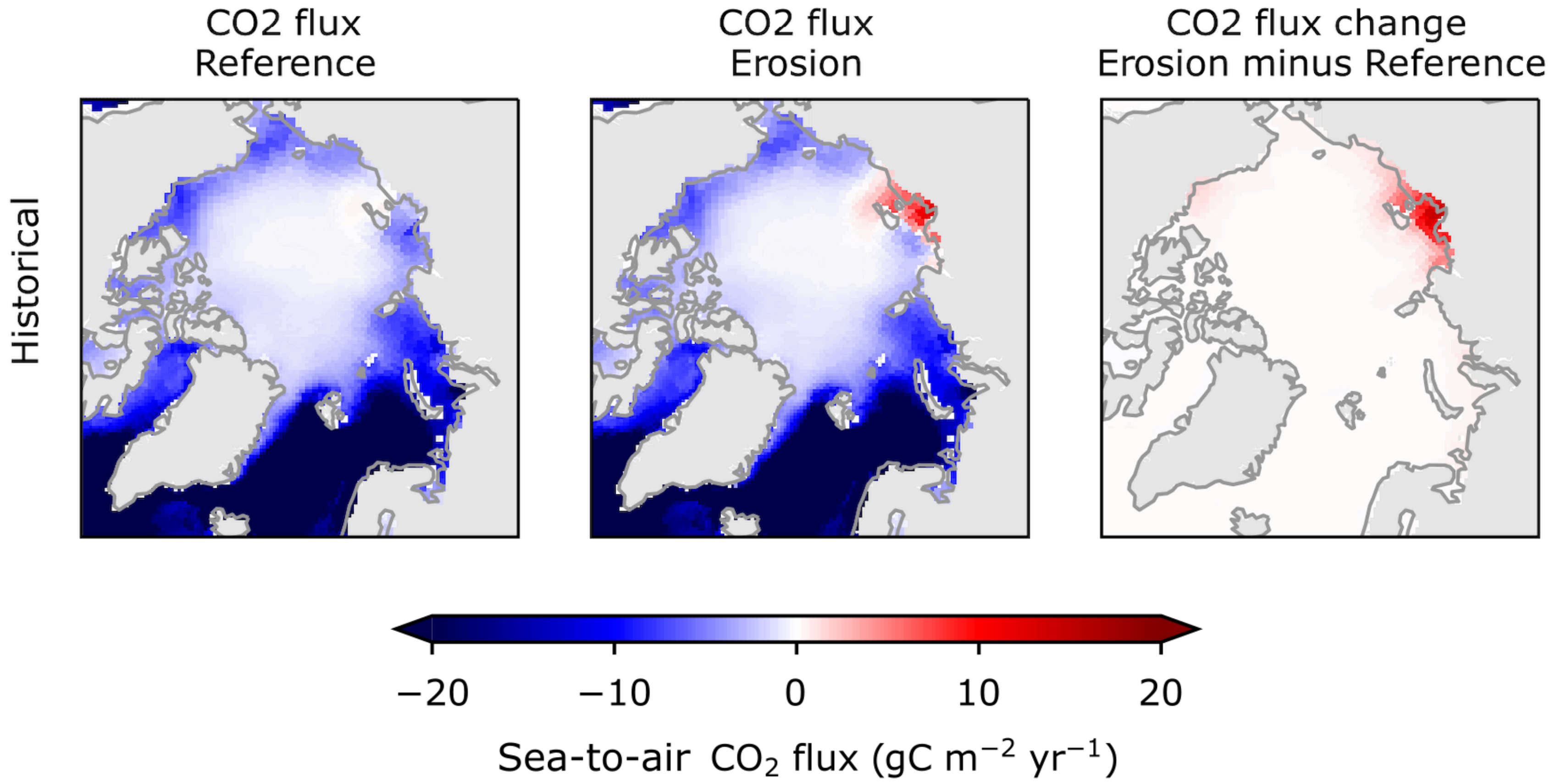
Sensitivity of CO_2 uptake change to erosion



0.6 (0.3 to 0.8)
0.6 (0.4 to 0.8)
0.7 (0.4 to 1.0)
0.6 (0.3 to 0.8)

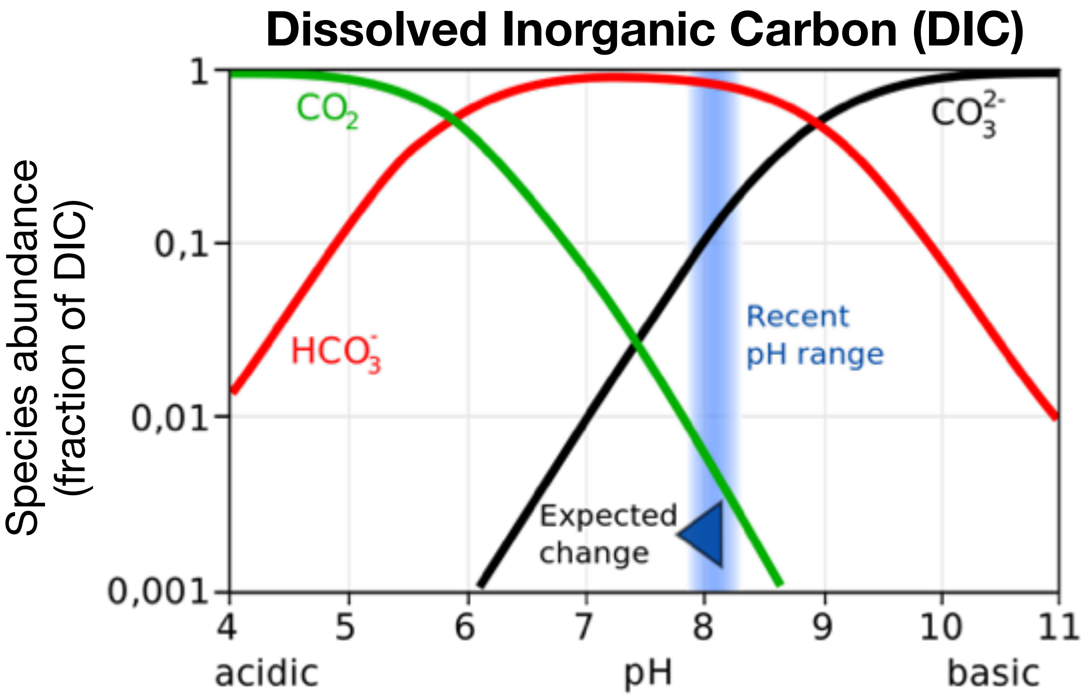
10%POC 10C/N
10%POC 14C/N
10%POC 18C/N
90%POC 10C/N
90%POC 14C/N
90%POC 18C/N
90%POC Marine
10%POC Marine

Erosion inverts the air-sea CO_2 flux direction on the Siberian shelf



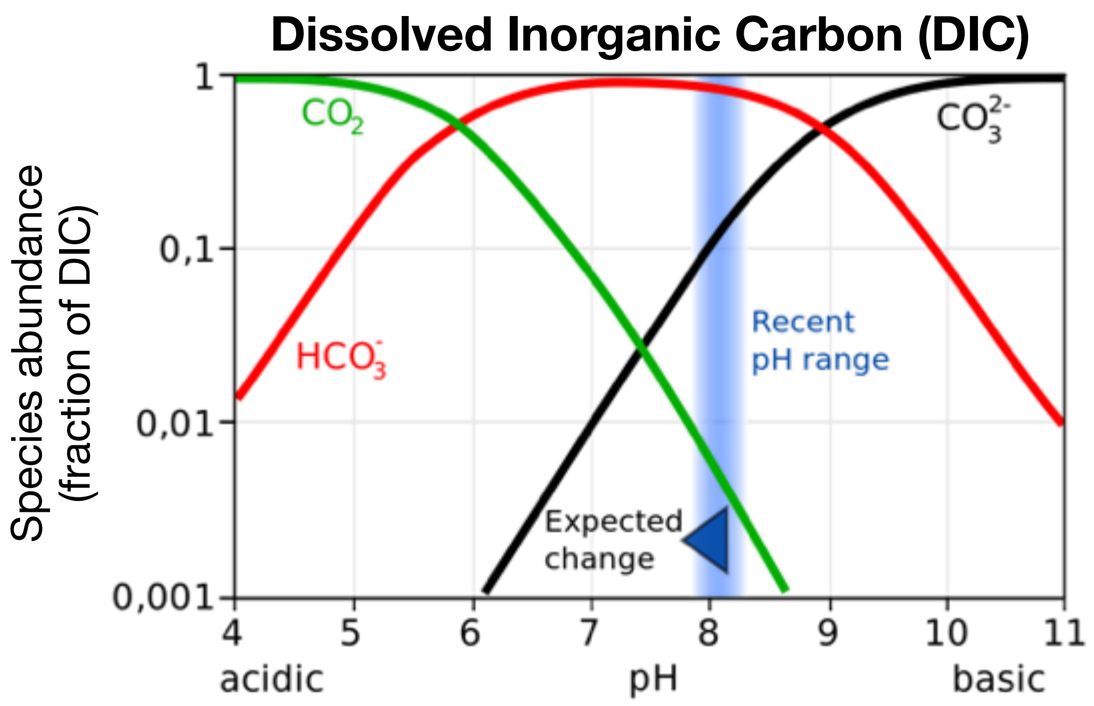
Nielsen *et al.* (in prep.)

Mechanisms of pCO_2 change in the Ocean



Schubert *et al.* (2006)

Mechanisms of pCO_2 change in the Ocean



Schubert *et al.* (2006)

↑DIC → ↑pCO_2

↓Alkalinity → ↑pCO_2

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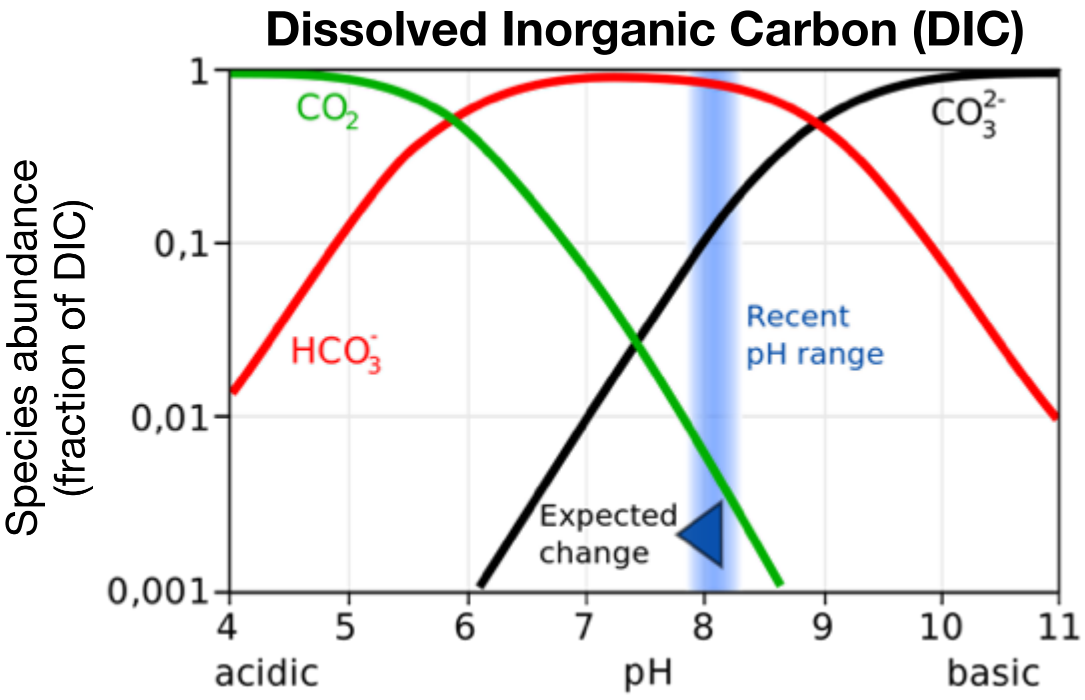


Schubert *et al.* (2006)

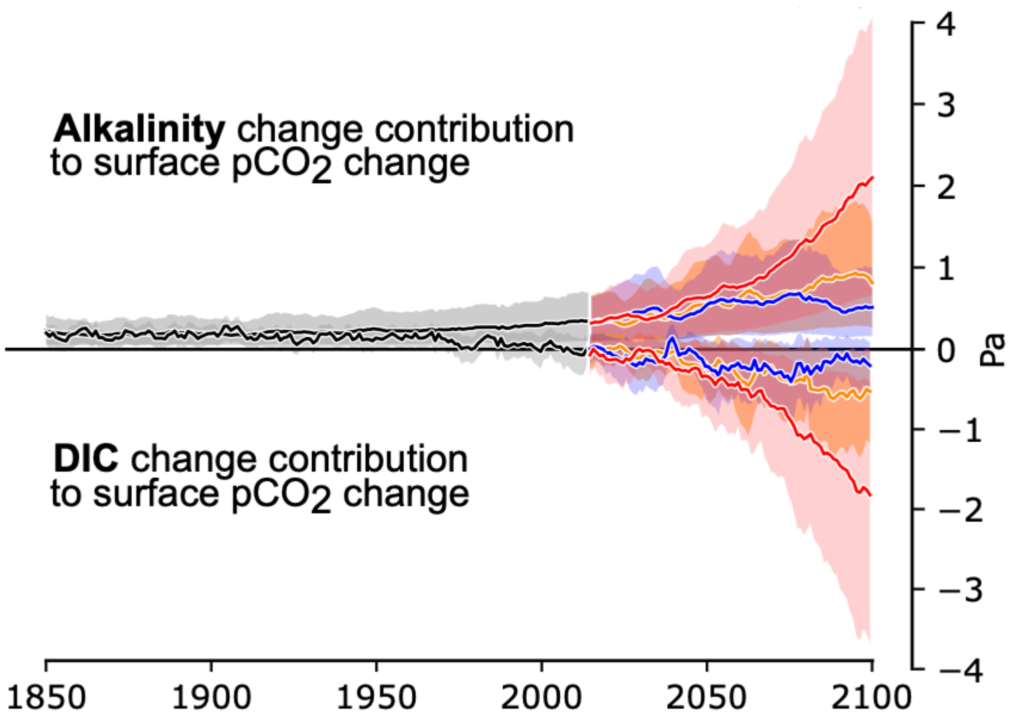
↑DIC ⟶ ↑pCO_2

↓Alkalinity ⟶ ↑pCO_2

Organic matter remineralization

$$C_{122}H_{263}O_{74}N_{16}P + 172O_2 \rightarrow \overset{\uparrow pCO_2}{122CO_2} + 16NO_3^- \overset{\uparrow pCO_2}{+ 16H^+} + H_3PO_4 + 122H_2O$$

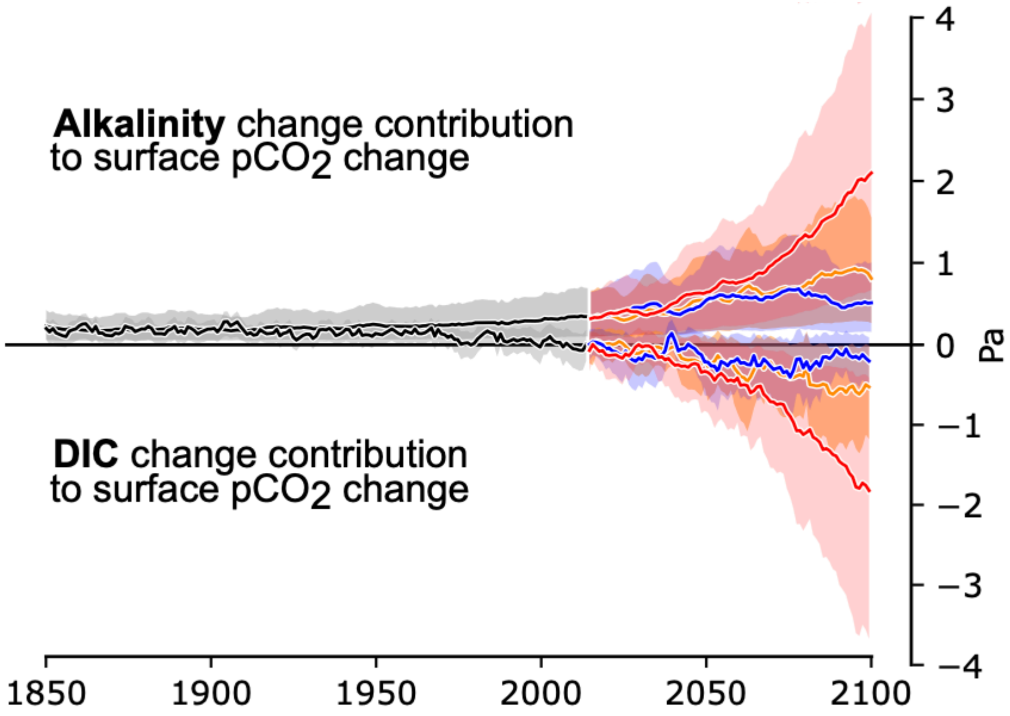
Decomposing pCO_2 in contributions from alkalinity and DIC



- Alkalinity decreases (OM remineralization) and decreases the Ocean's ability to take up CO_2

Nielsen *et al.* (in prep.)

Decomposing pCO_2 in contributions from alkalinity and DIC



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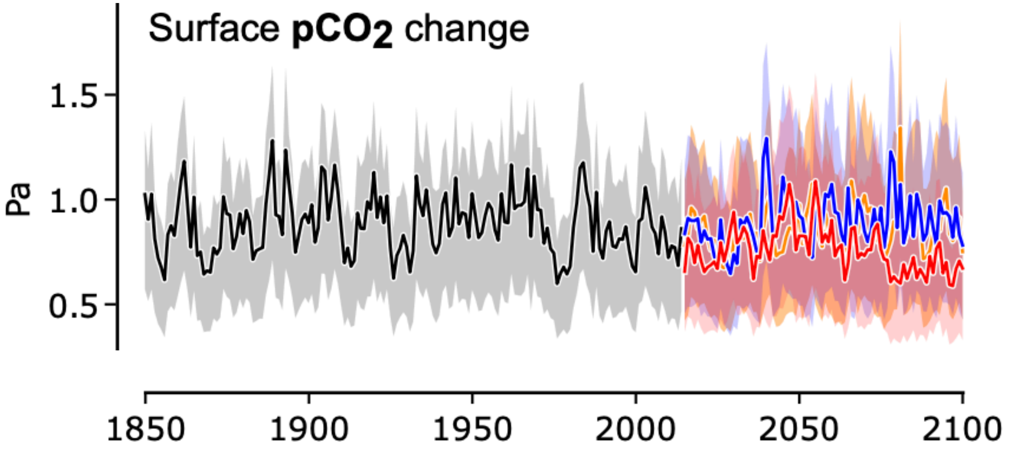
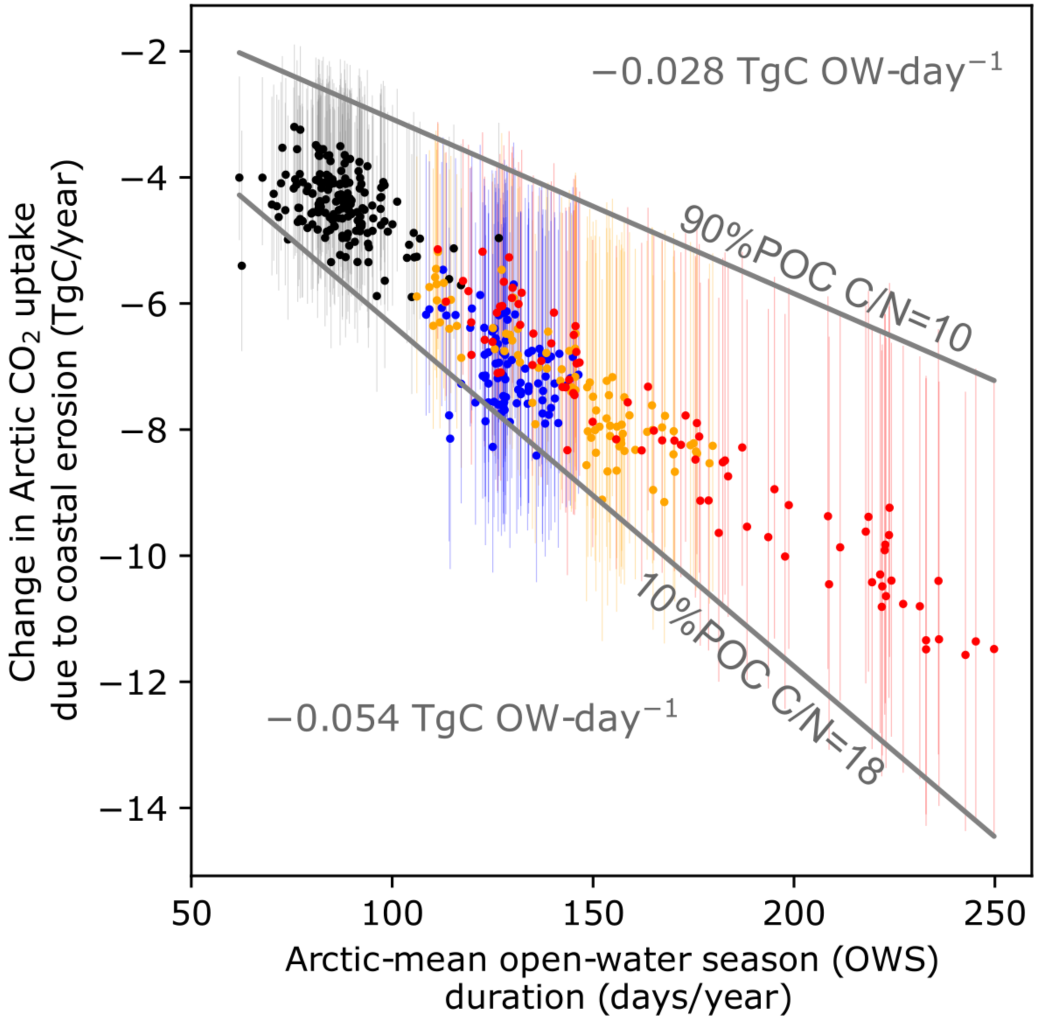


- Alkalinity decreases (OM remineralization) and decreases the Ocean's ability to take up CO_2
- The combined effect of decreasing alkalinity and DIC maintain a constant surface pCO_2 increase

Nielsen *et al.* (in prep.)

Sea-ice modulates the impact of erosion on CO_2 uptake



Nielsen *et al.* (in prep.)

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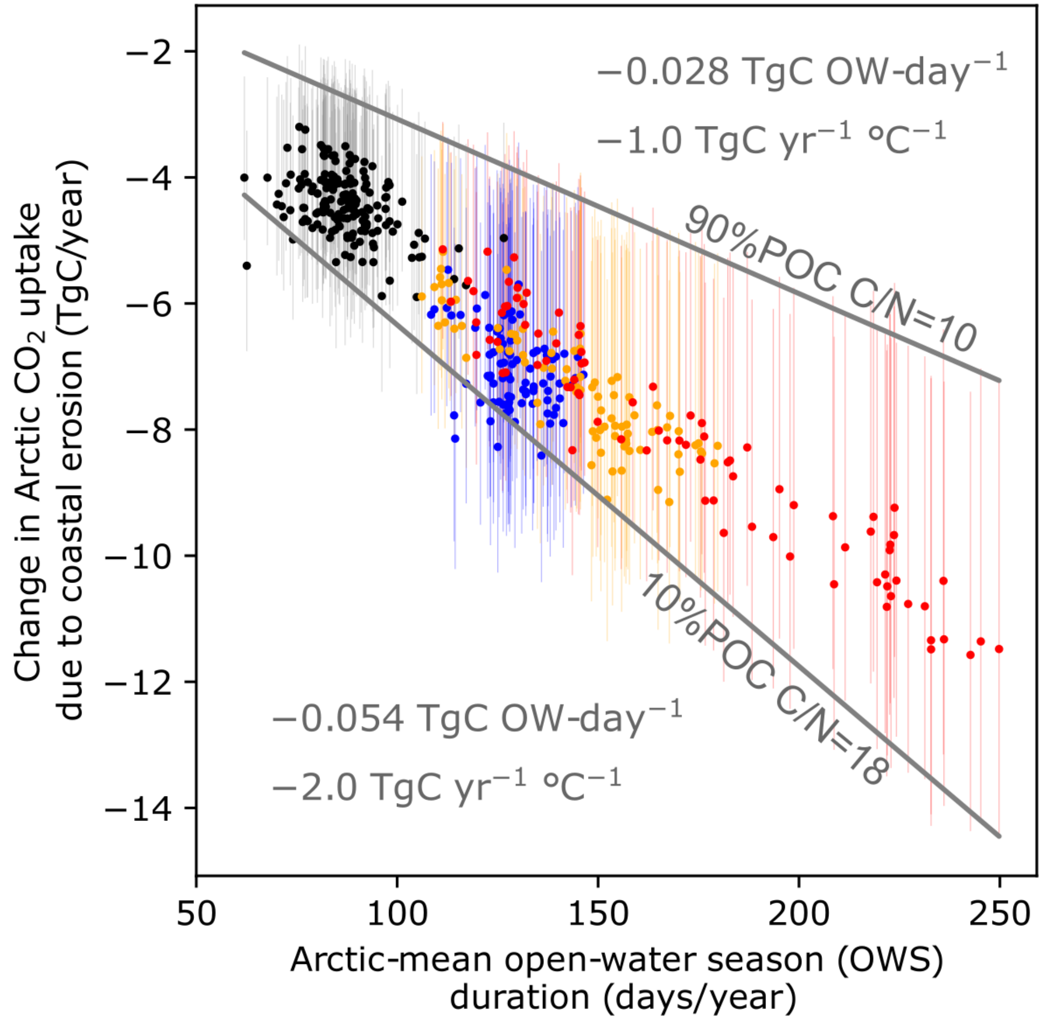

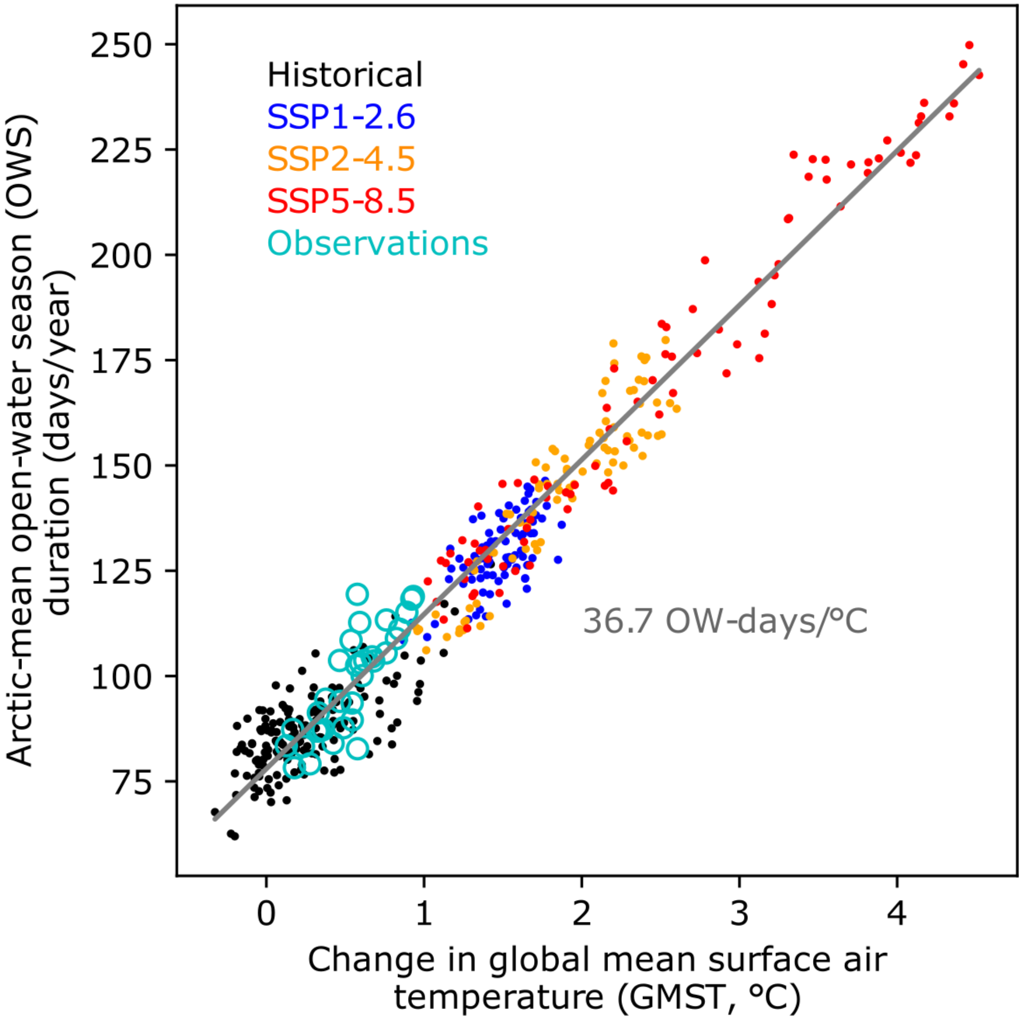

Nielsen *et al.* (in prep.)

Summary

- Simple, semi-empirical model for Arctic coastal permafrost erosion compatible with ESMs

Summary

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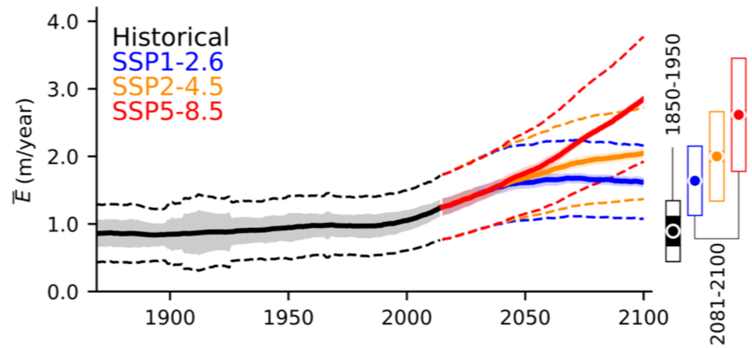

Summary

- Simple, semi-empirical model for Arctic coastal permafrost erosion compatible with ESMs
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  - **15(±5)%** of Inner Arctic uptake in the historical period
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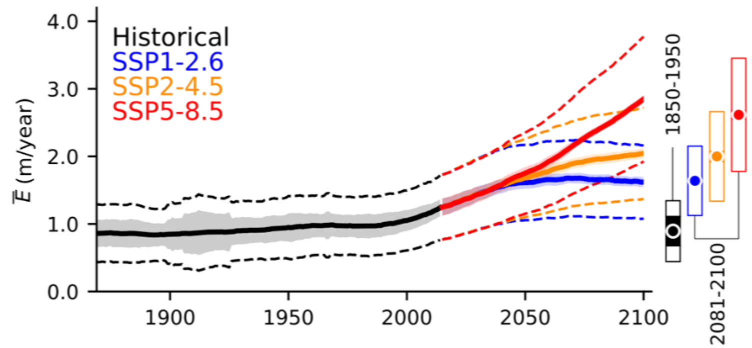

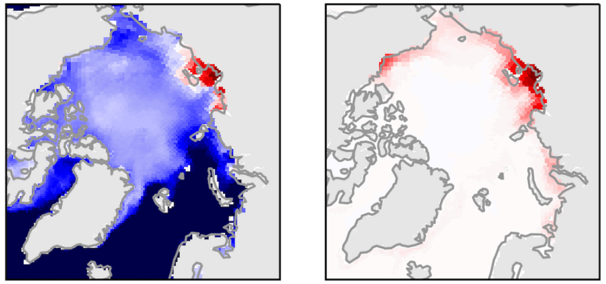

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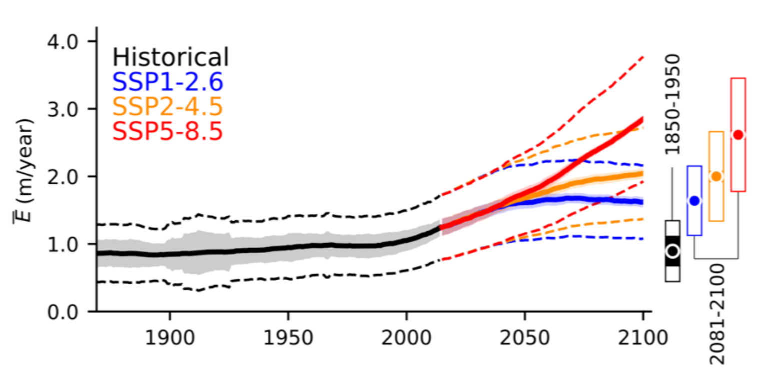
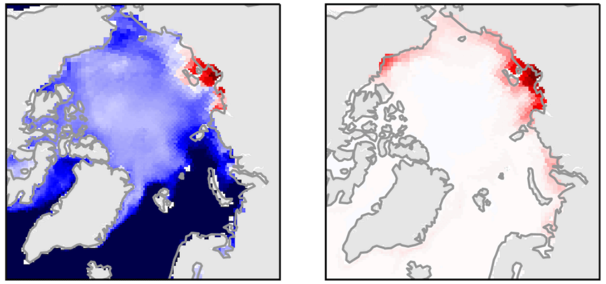
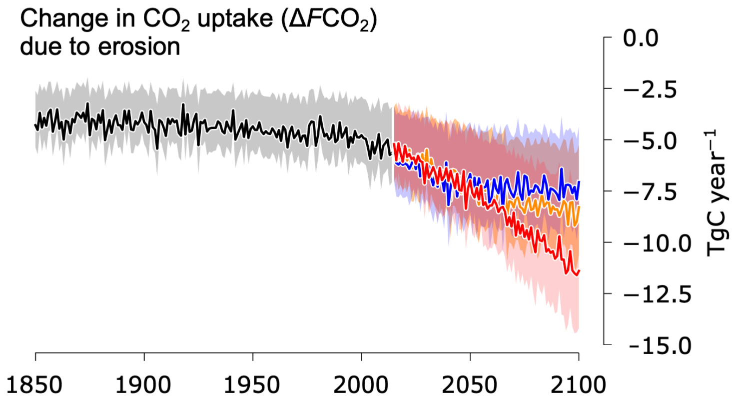
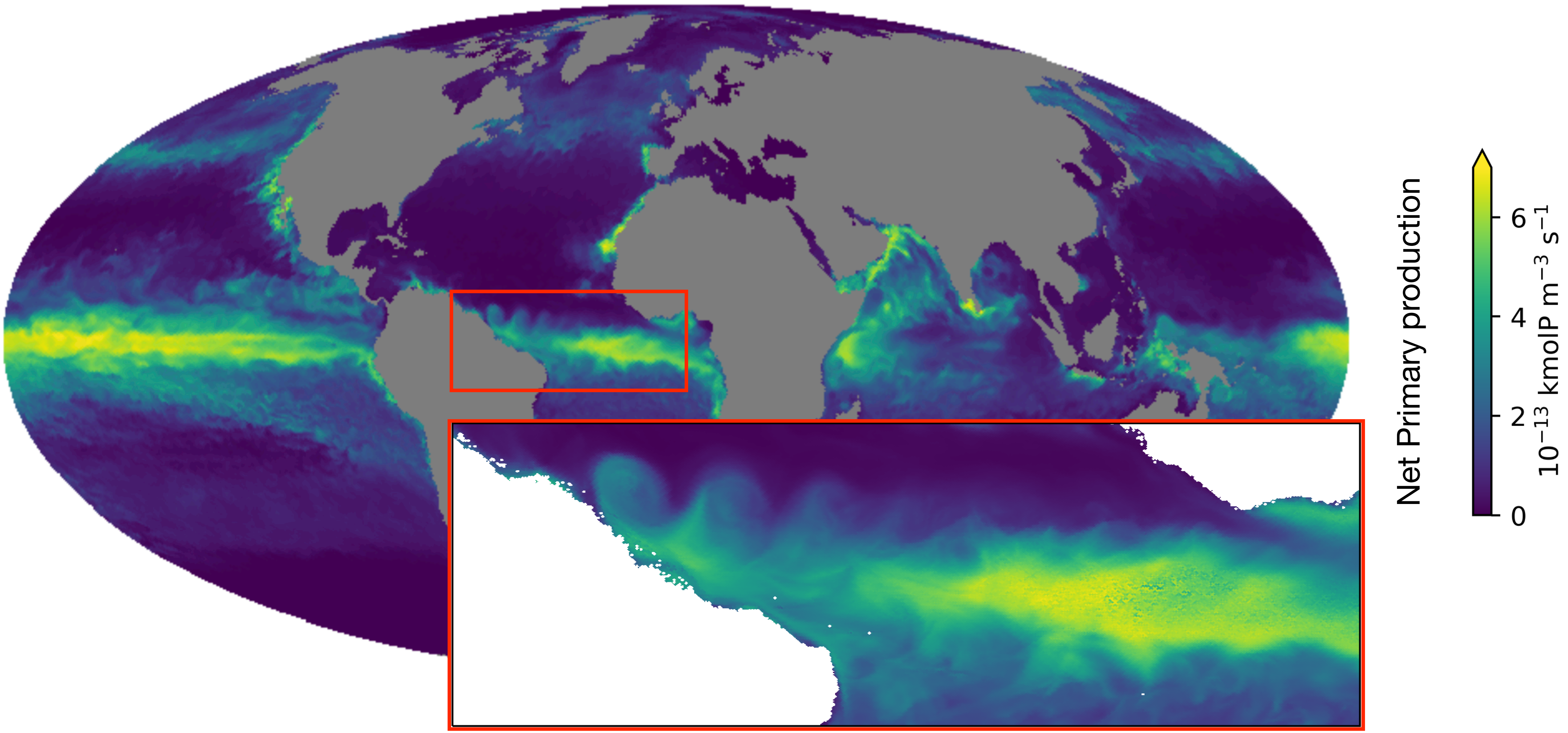


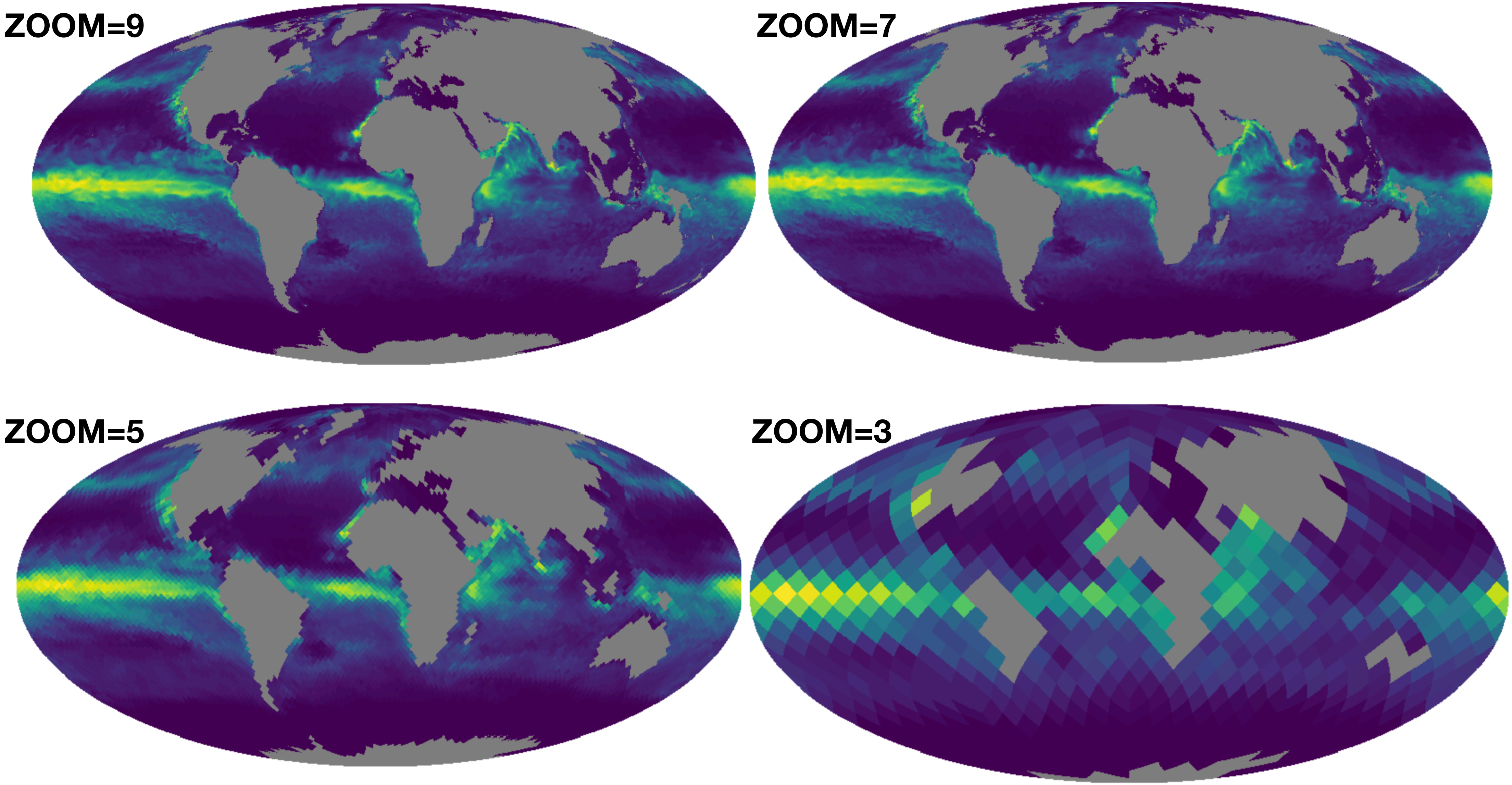




Global, km-scale ICON-ESM with Ocean Biogeochemistry



HEALPix (Hierarchical Equal Area isoLatitude Pixelation)



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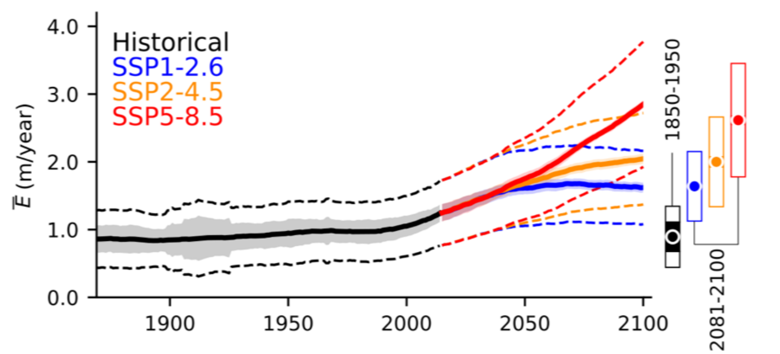
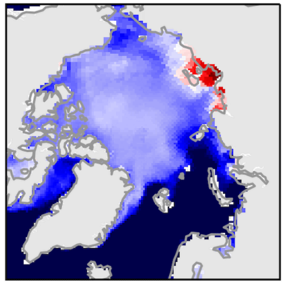
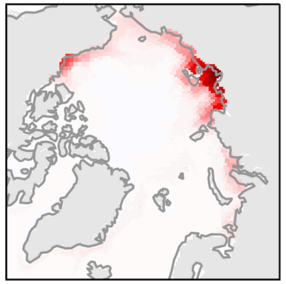
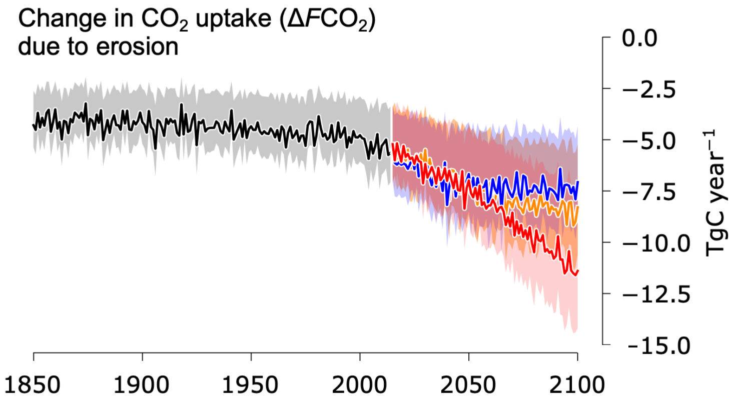








Thank you!

Extra slides

A simple, semi-empirical model for Arctic coastal erosion

as a linear combination of the thermal and mechanical drivers of erosion, compatible with ESM simulations

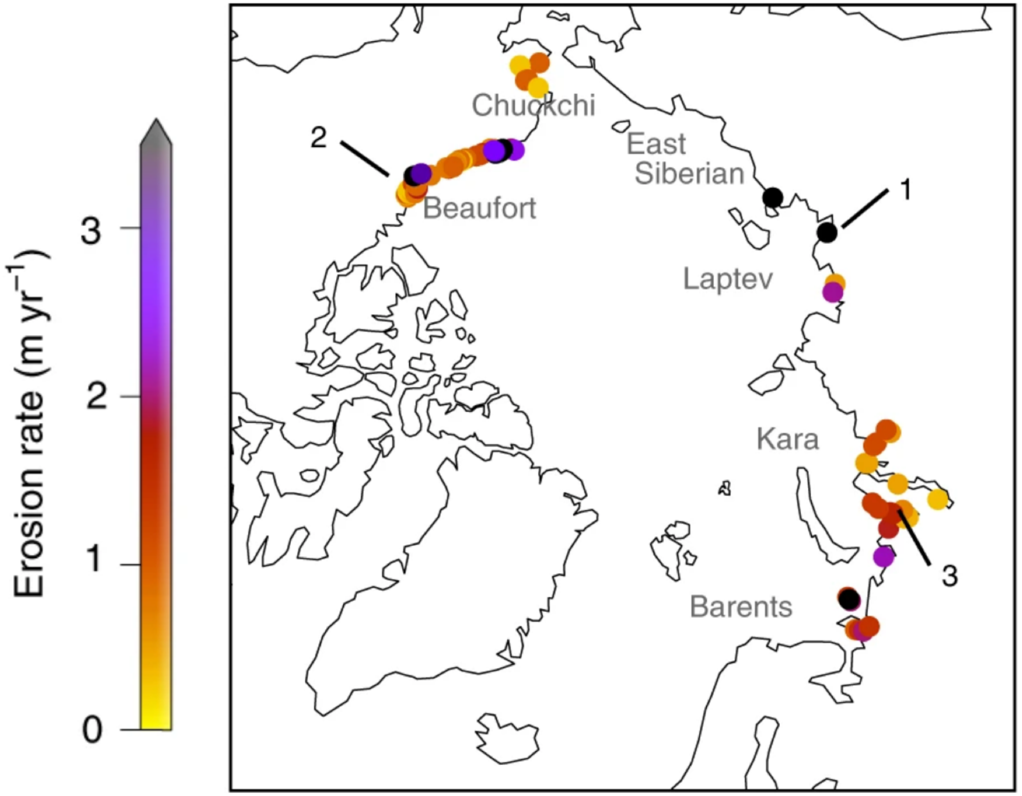
$$E(x,t) = \underbrace{\overline{E}(t)}_{\text{Temporal}} + \underbrace{\Delta E(x,t)}_{\text{Spatial}}$$

$$E(x,t) = 0 \text{ if } \mathbf{SIC}(x,t) \geq 15\%$$

$$\overline{E}(t) = \underbrace{a_{TD}\,\overline{T}(t)}_{\text{Thermal}} + \underbrace{a_{TA}\,\overline{H}(t)}_{\text{Mechanical}}$$

$\Delta E(x,t) =$ Linear regression of **waves, temperature** and **ground ice**

ACD database (Lantuit et al. 2012)
"High-quality" segments

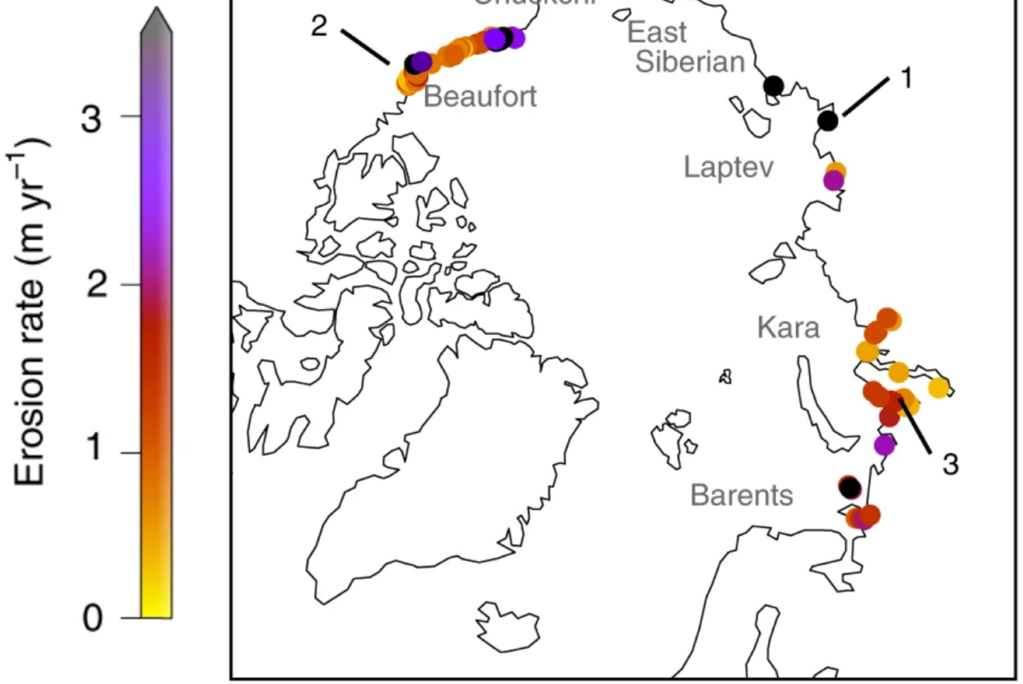


1: Bykovsky Peninsula and Muostakh Island
2: Mackenzie River Delta region
3: Yamal Peninsula

The Spatial Component

$$\Delta E(x,t) = \begin{cases} b_\theta \Delta\theta(x) + b_H \Delta H_{\text{day}}(x,t) & \text{if } E_{\text{obs}}(x) < 2.5 \text{ m yr}^{-1} \\ b'_\theta \Delta\theta(x) + b_T \Delta T_{\text{day}}(x,t) & \text{otherwise} \end{cases}$$

ACD database (Lantuit et al. 2012)
Trained on "High-quality" segments



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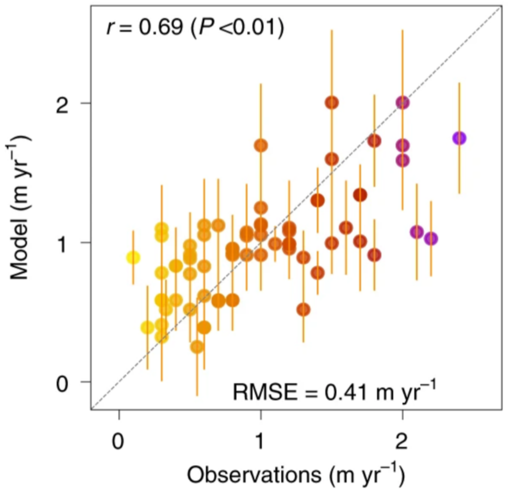
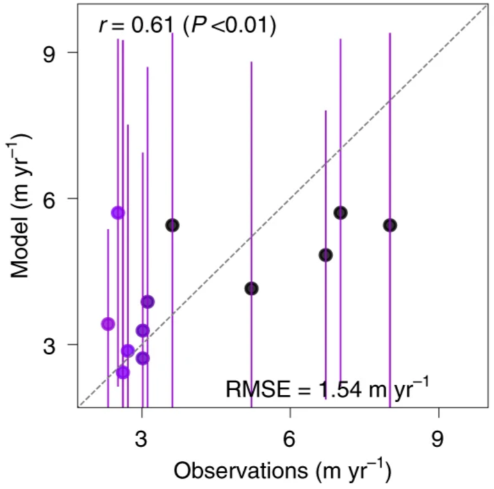


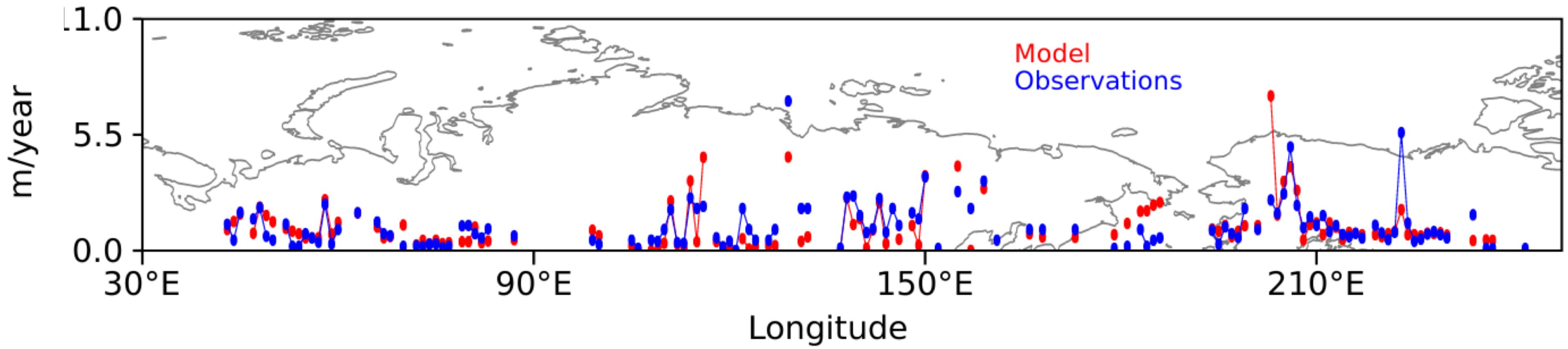
Non-extreme:
waves +
ground ice



Extreme:
temperature +
ground ice

Assumptions

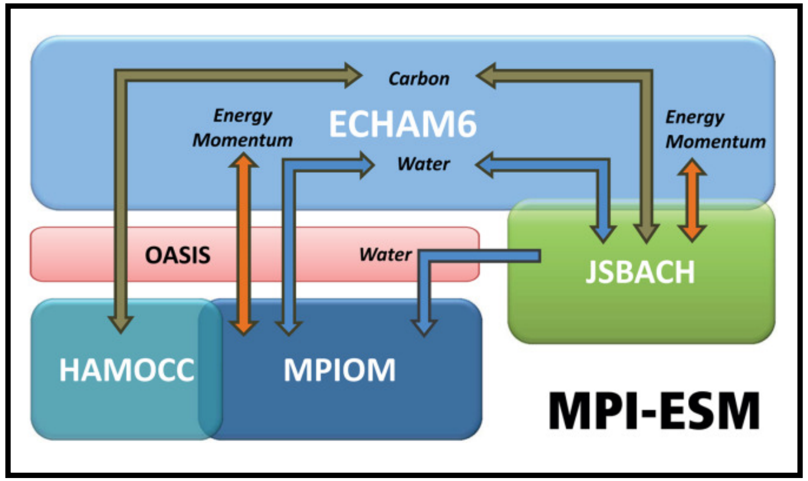
- Only the erosive coastal segments from the ACD (306 out of 1314)
- Only linear additive effect of the thermal and mechanical drivers
  - i.e.: absence of non-linear, synergistic effects
- Ground-ice is constant in the future
- Linear regression model trained with observations is valid in the future



Forcing:

- 10-member Ensemble of MPI-ESM from CMIP6 (Historical and Scenarios)
- Ocean surface waves (WAM)

Earth system model (ESM) simulations including erosion



Giorgetta *et al.* (2013)

Changes in ocean biogeochemistry, air-sea CO_2 fluxes

?

Nielsen *et al.* (in prep.)

Carbon Flux (TgC/**day**)

Sea ice, winds

Wave Model (WAM)

Waves

Temperature, sea ice

Coastal Erosion Model

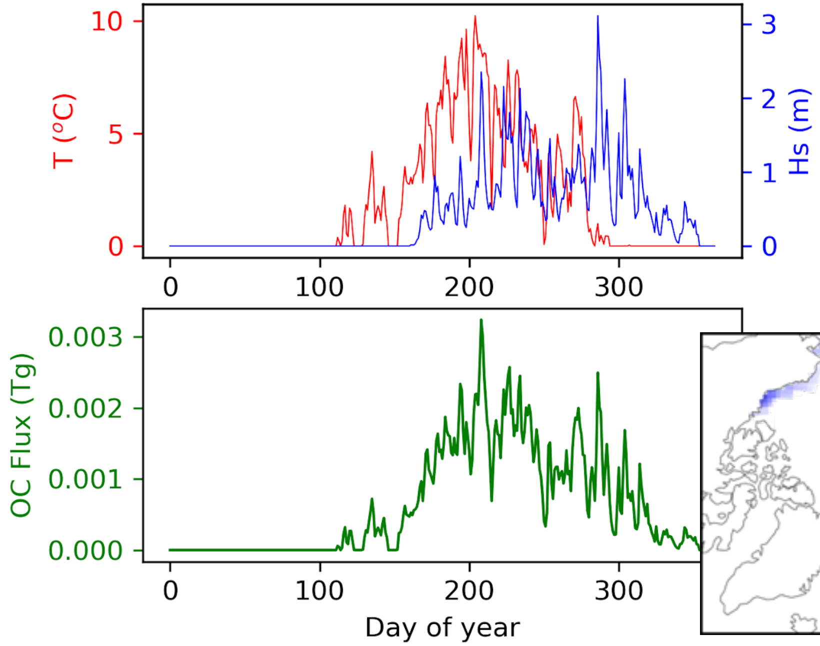
Ground ice

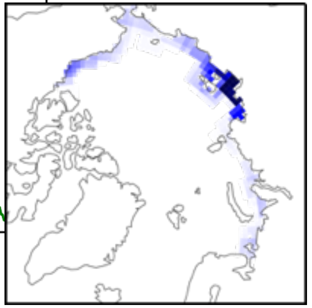
ACD Database

Elevation, Length, Ground ice, Carbon content

Erosion Rates (m/year)

Carbon Flux (TgC/**year**)

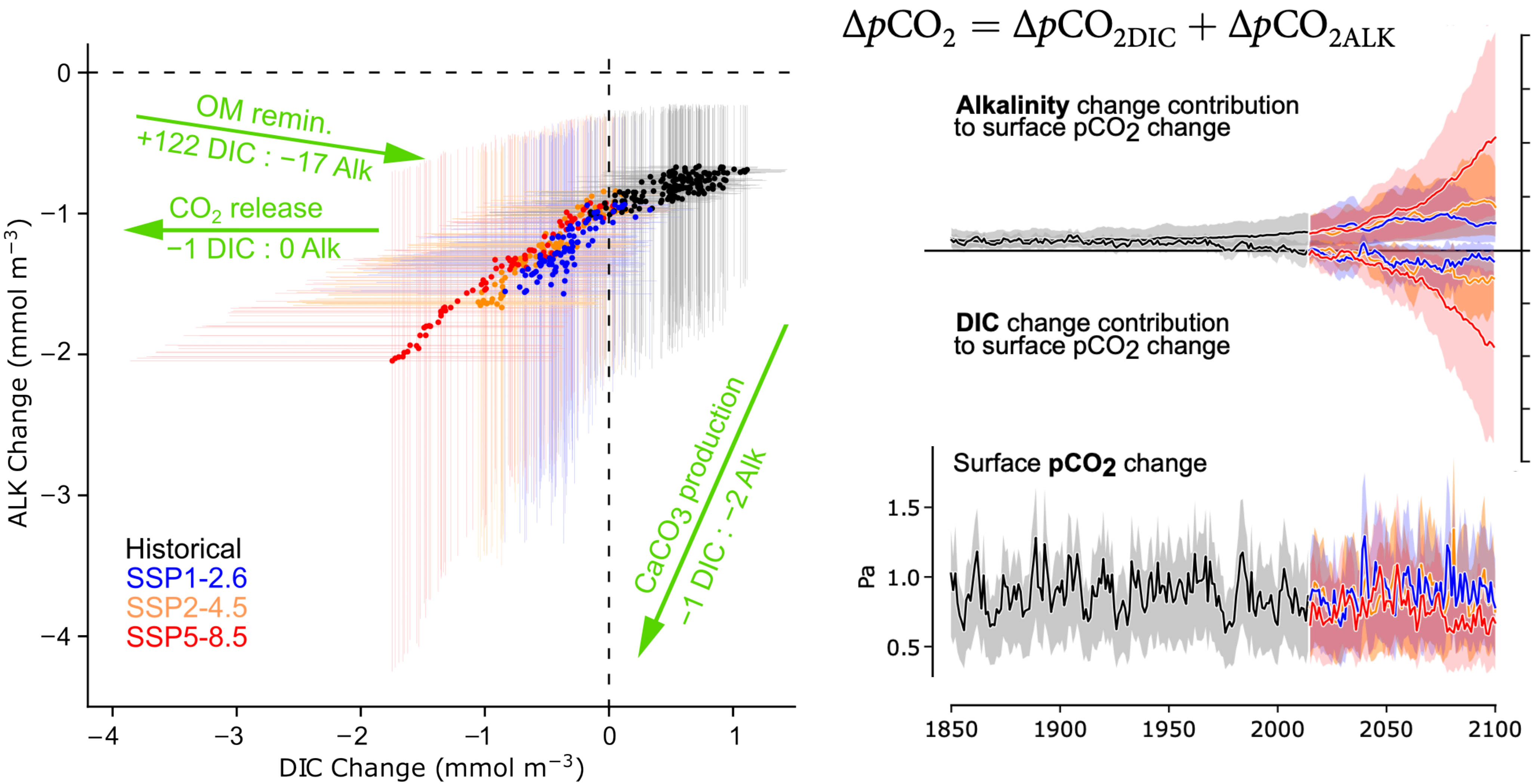




Nielsen *et al.* (2022)

Alkalinity and DIC response to coastal erosion

Changes in alkalinity and DIC maintain a relatively constant increase in surface pCO_2



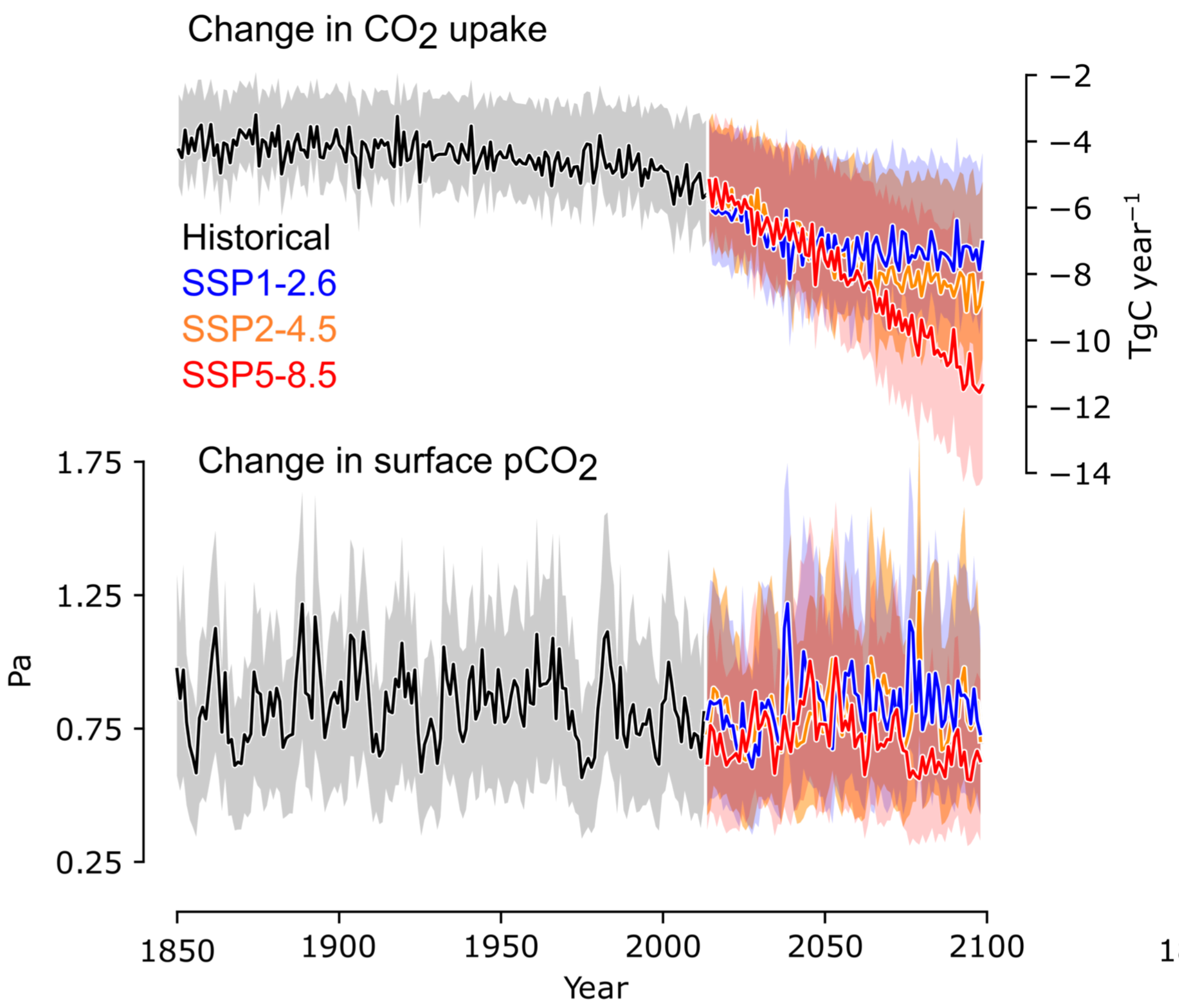
Nielsen *et al.* (in prep.)

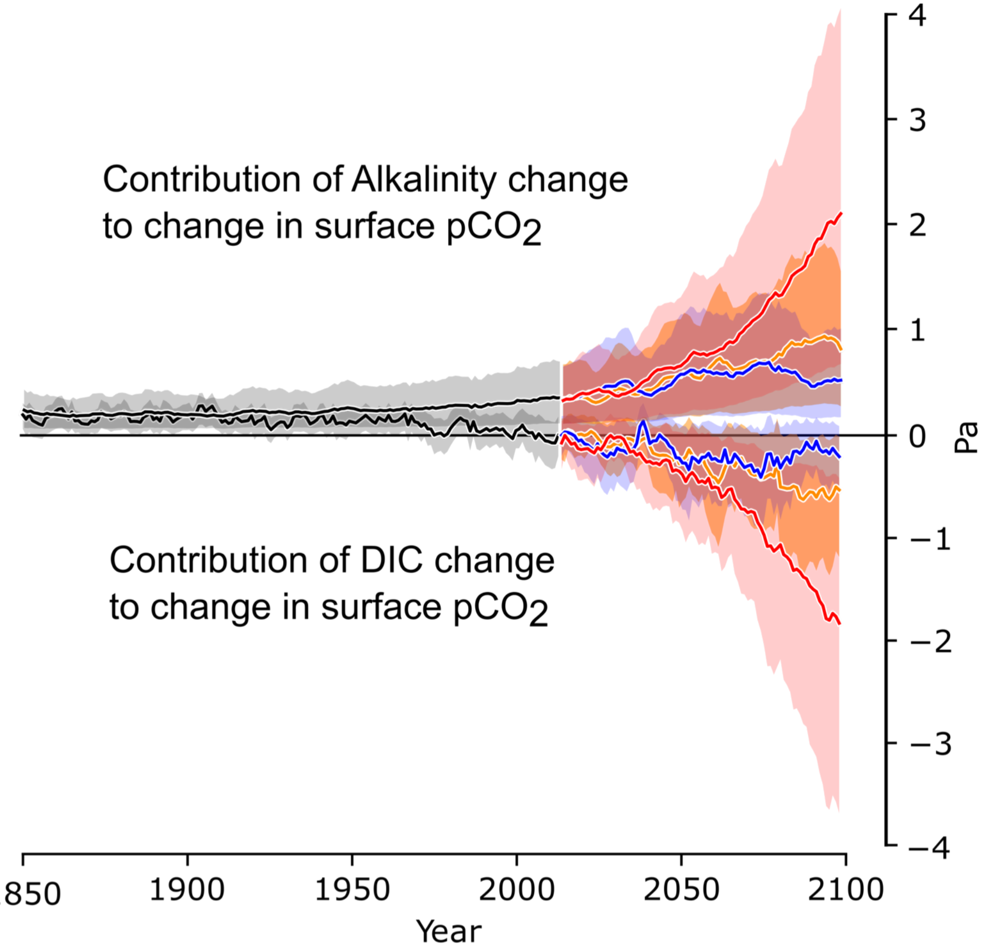
Decomposing ΔpCO_2

$$\boxed{\Delta pCO_2 = \Delta pCO_{2DIC} + \Delta pCO_{2ALK}} + \cancel{\Delta pCO_{2SST}} + \cancel{\Delta pCO_{2SSS}}$$

Same physics

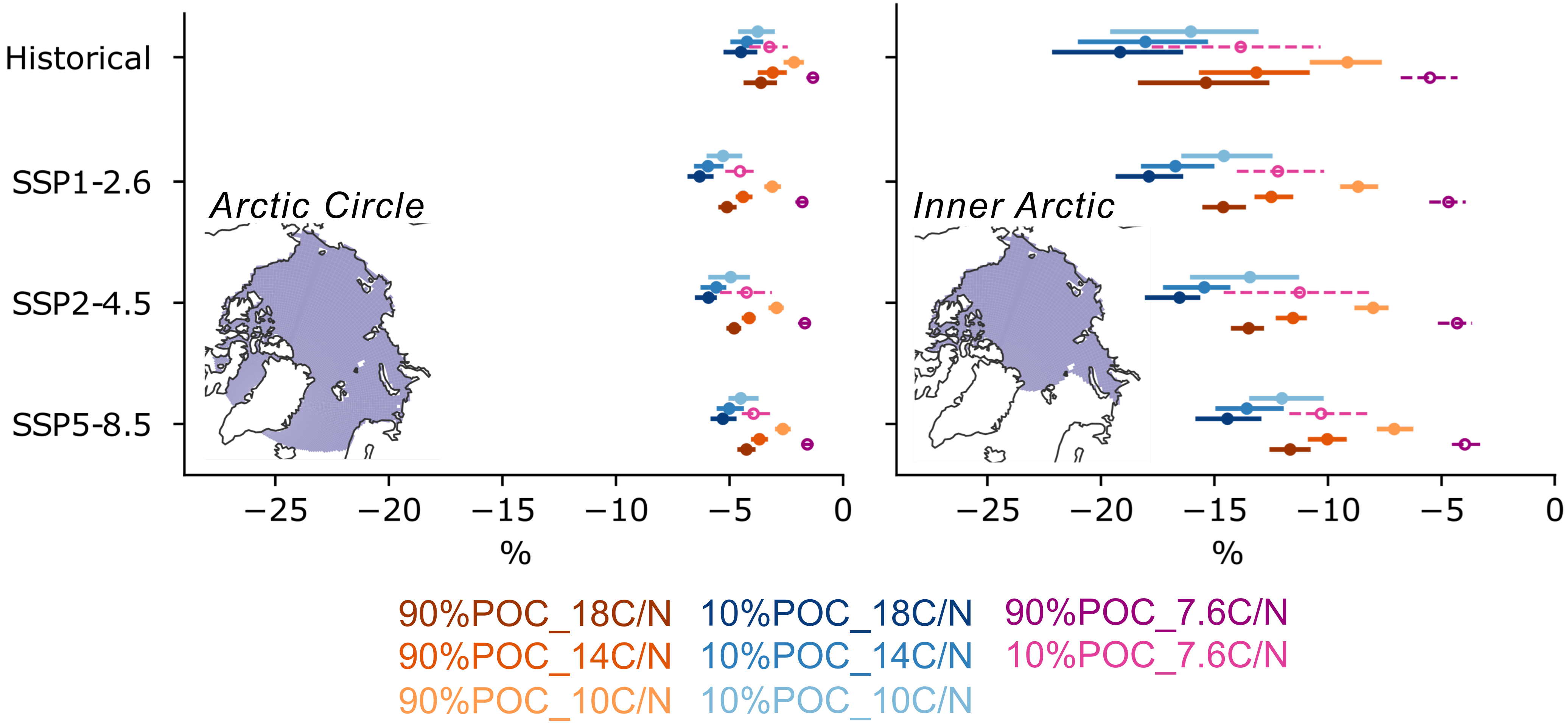
$$\Delta pCO_{2X} = \Delta X * \gamma_X * pCO_{2Ref}/\overline{X}$$



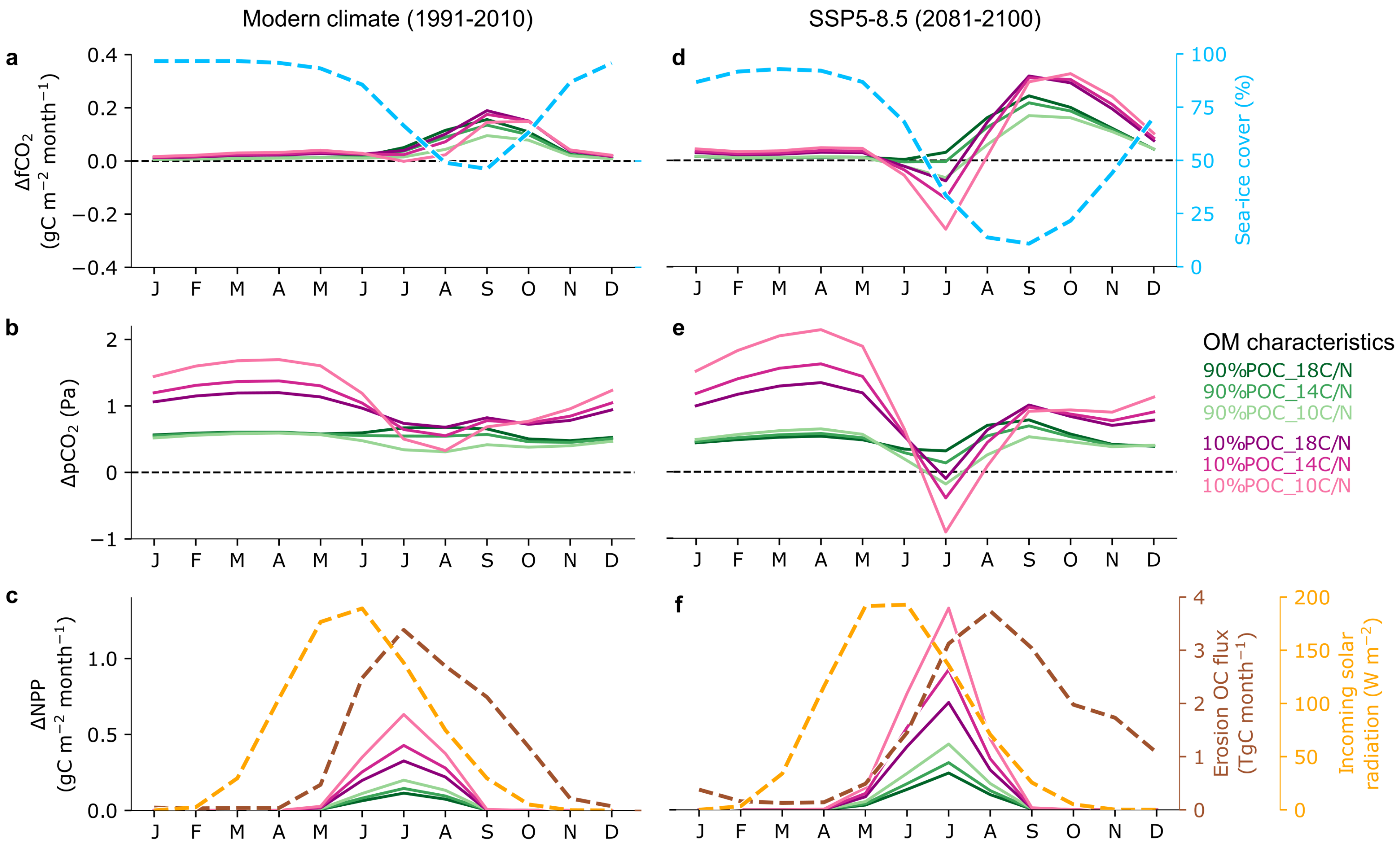


Coastal erosion reduces the Arctic Ocean's CO_2 uptake

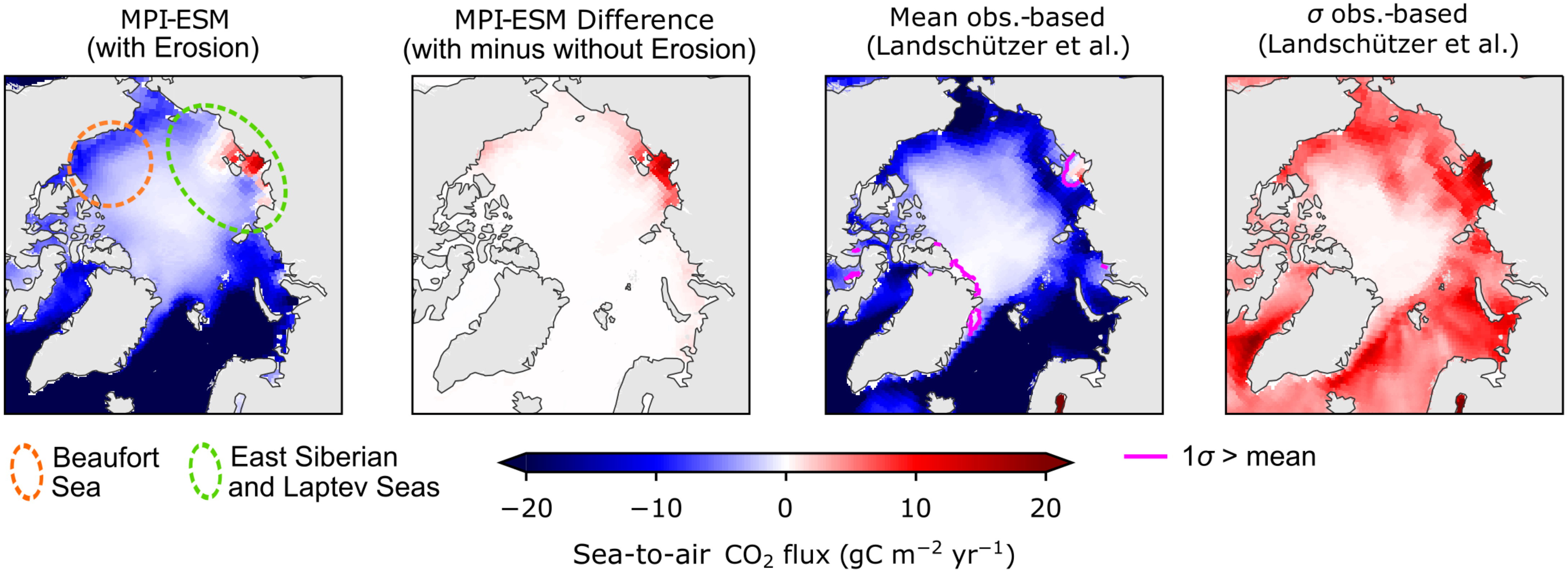
Percentage change in surface CO_2 uptake due to coastal erosion



Seasonal cycle

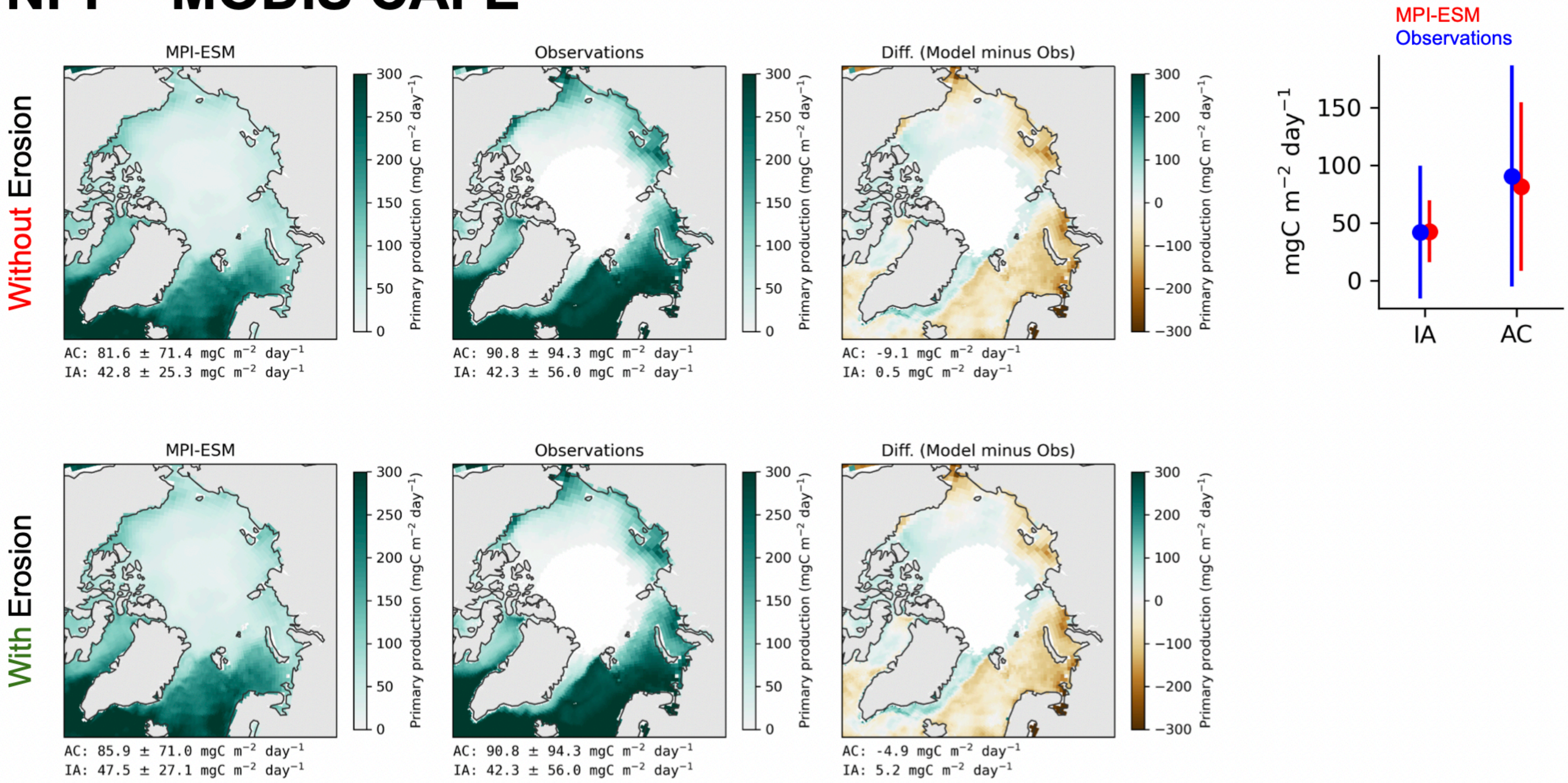


Erosion inverts the air-sea CO_2 flux direction on the Siberian shelf

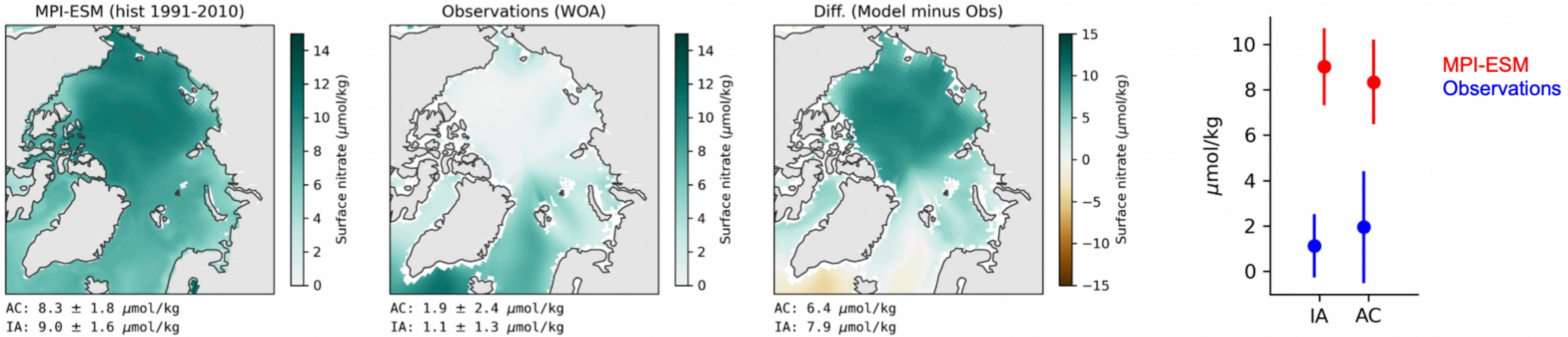


Nielsen *et al.* (in prep.)

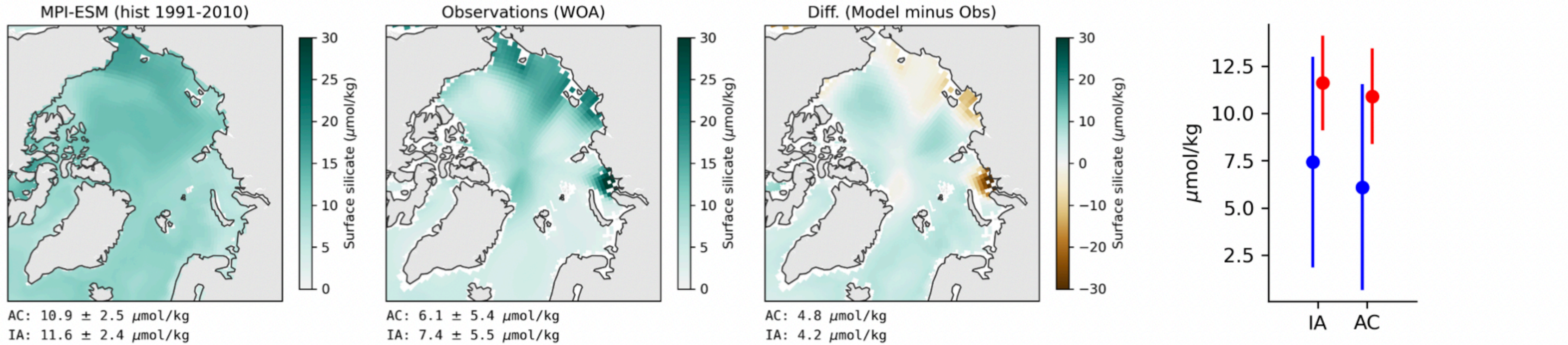
NPP - MODIS CAFE



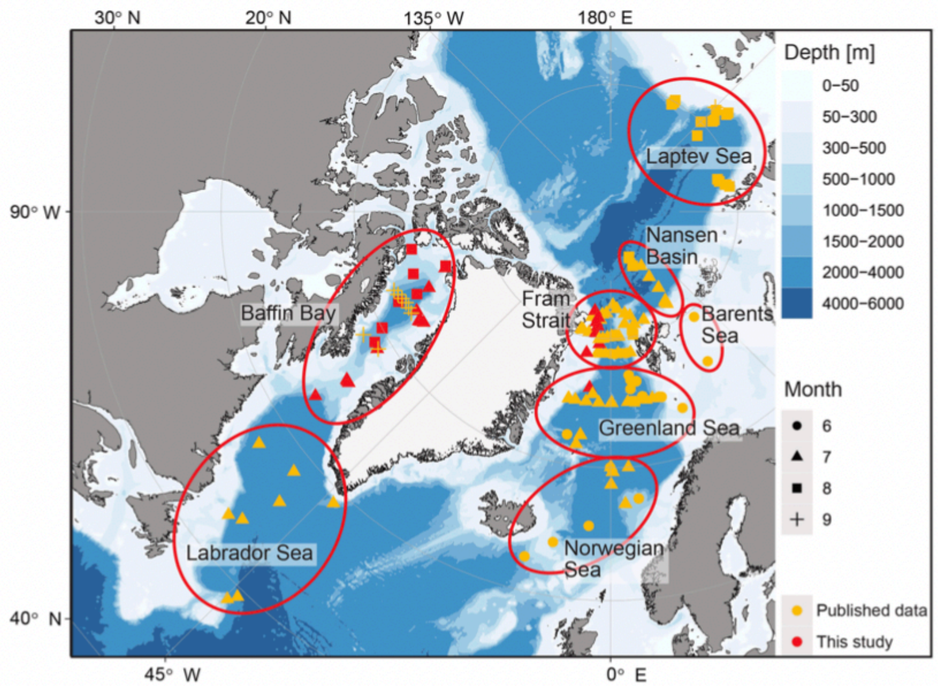
Surf. Nitrate (WOA)

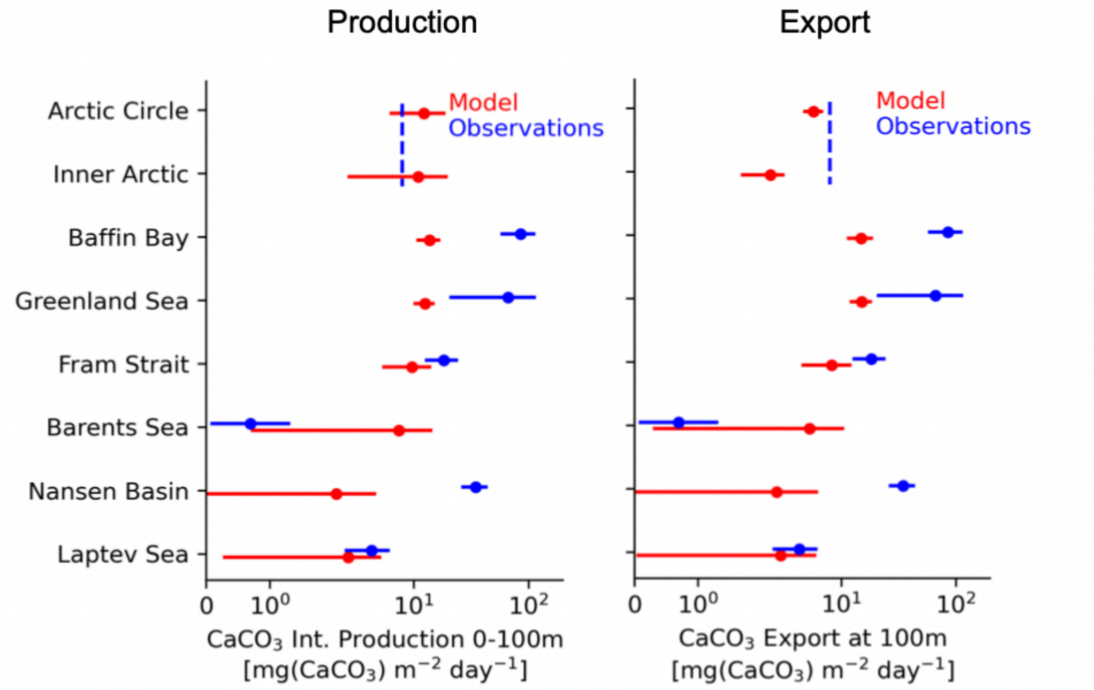


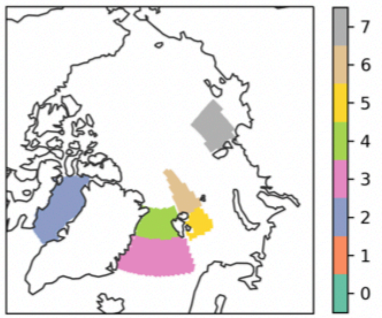
Surf. Silicate (WOA)



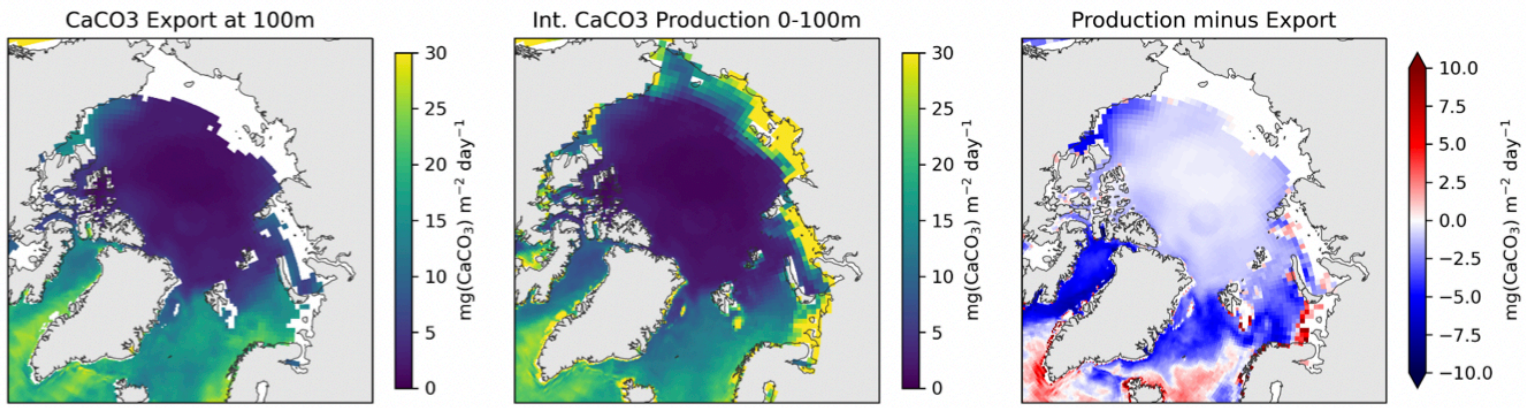
CaCO3 Production





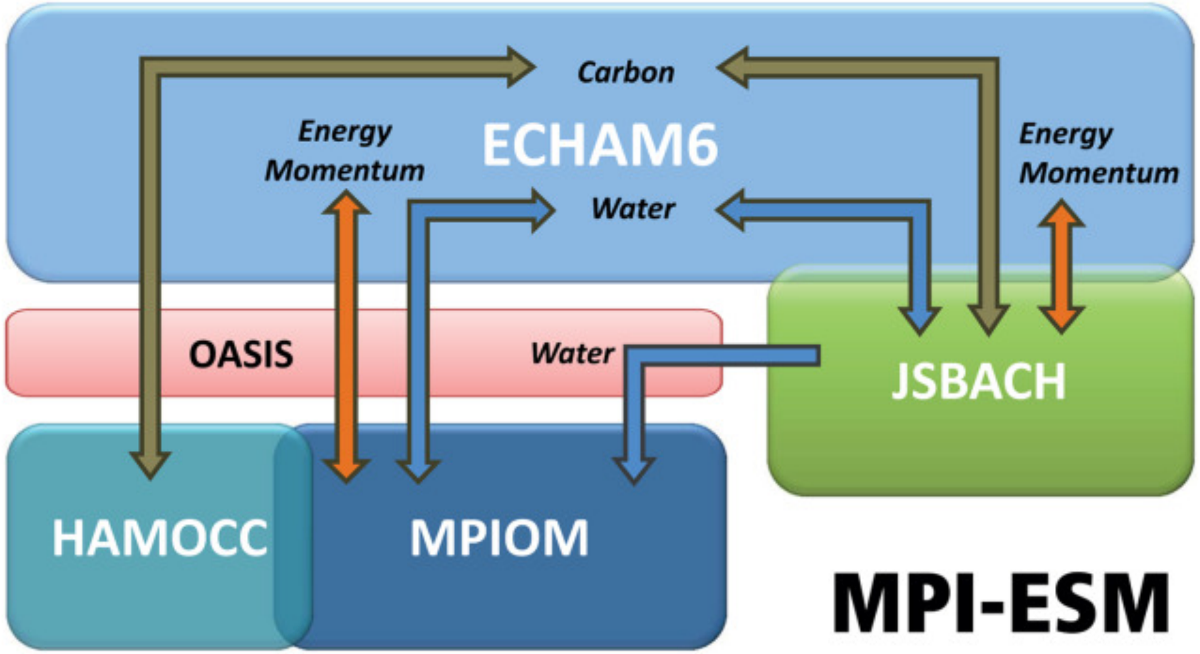


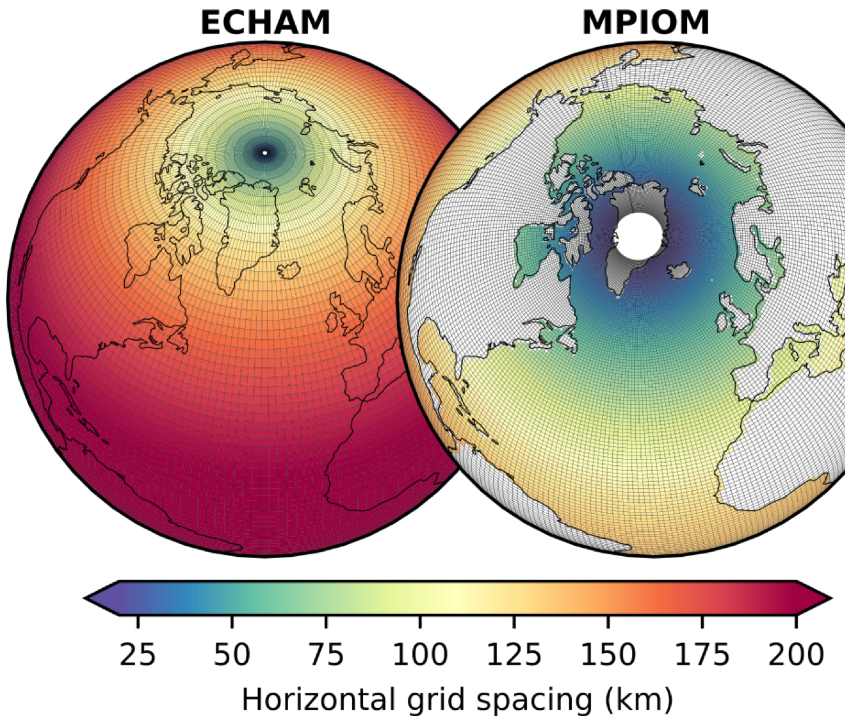
Tell, F., Jonkers, L., Meilland, J., and Kucera, M. (2022) Upper-ocean flux of biogenic calcite produced by the Arctic planktonic foraminifera *Neogloboquadrina pachyderma*, Biogeosciences, 19, 4903–4927, https://doi.org/10.5194/bg-19-4903-2022



Max Planck Institute Earth System Model (MPI-ESM)

MPI-ESM simulates the global Land, Ocean and Atmosphere, representing the main fluxes of water, energy and carbon. Scenario simulations require spatial resolution on the order of 10-100 kilometers.





Schematics of fluxes between components in MPI-ESM
(Giorgetta et al. 2013, https://doi.org/10.1002/jame.20038)